NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE

FIVE-YEAR SCIENCE PLAN

MULTI-HAZARD RESEARCH TO MAKE A MORE RESILIENT WORLD

SECOND EDITION
JANUARY 2020

NHERI
Natural Hazards Engineering Research Infrastructure

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Cover: Satellite image of Hurricane Katia (left) making landfall over the Mexican state of Veracruz, Hurricane Irma (center) approaching Cuba, and Hurricane Jose reaching peak intensity on September 8, 2017 (Photo: VIIRS image from NOAA View Global Data Explorer).

Grant Listing

The following awards from the National Science Foundation support the Natural Hazards Engineering Research Infrastructure (NHERI):

FLORIDA INTERNATIONAL UNIVERSITY
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LEHIGH UNIVERSITY
Experimental Facility with Large-Scale Multi-Directional Hybrid Simulation Testing Capabilities (NSF award #1520765)

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UNIVERSITY OF TEXAS AT AUSTIN
Large Mobile Shakers (NSF award #1520808)

UNIVERSITY OF WASHINGTON
RAPID Facility (NSF award #1611820)

Foreword

This is the second edition of the five-year Science Plan for the Natural Hazards Research Infrastructure (NHERI). It provides information for constituents, including practitioners, as well as guidance for members of the research community.

This report is an overview of the research needed to support the Grand Challenges described by the report. It covers both the scope and the process of conducting multi-hazard research for improving civil infrastructure.

The first Grand Challenge focuses on identifying and quantifying characteristics of earthquakes, windstorms, storm surge, tsunamis and waves. The second assesses the physical vulnerability of civil infrastructure and social vulnerability of populations exposed to these hazards. The third Grand Challenge creates technologies and tools to design, construct and maintain sustainable infrastructure for the nation.

The report addresses five Key Research Questions at the cusp of emerging transformative discoveries to meet the Grand Challenges. Each Key Research Question is supported with example research topics that will help answer these research questions.

Importantly, Appendix A provides examples of research campaigns that could be developed into full research programs that address the Grand Challenges in earthquakes, wind events, tsunamis and other coastal hazards.

Appendix B gives a brief description of the objectives, capabilities and research opportunites at each of the NHERI Experimental Facilities and components.

The following members of the Science Plan Task Group guided the development of the 2nd edition of the five-year NHERI Science Plan with the support of members of the Network Coordination Office.

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Civil infrastructure shelters and sustains individuals and communities. It is built on a network of facilities and services that includes housing, business, water, gas, electricity, sanitation, communications, transportation, and institutions such as schools and hospitals.

All are interconnected and must be designed, constructed, and maintained with the expectation that they will provide adequate performance when subjected to earthquakes, windstorms, and related natural hazards of tsunami and storm surge.

The failure of civil infrastructure adds considerable strain to communities and puts lives, health, and societal functions at risk. However, when civil infrastructure is built to withstand natural hazards it can help reduce vulnerability and enhance societal resilience.

Introduction

The Natural Hazards Engineering Research Infrastructure (NHERI) is a distributed, multi-user, national facility that provides the natural hazards research community with state-of-the-art research infrastructure.

The National Science Foundation (NSF) funds NHERI. NHERI enables researchers to explore and test creative concepts to protect people and their homes, businesses, schools and infrastructure lifelines from earthquakes, tsunamis, and windstorms, including storm surges and waves. The results of this leading-edge research can help prevent natural hazards from becoming societal disasters.

The Science Plan[1] is posed as a set of three Grand Challenges with five Key Research Questions to guide NHERI research. It is anticipated that the research will deliver technical breakthroughs to improve the resilience and sustainability of existing and future civil infrastructure, also known as the built environment.

High priority research subject areas are provided for each of the Key Research Questions to assist future researchers respond to the Grand Challenges.

This edition of the Science Plan illustrates how powerful new technologies can empower researchers to accelerate the pace of innovation to achieve the goals of NHERI.

NHERI research infrastructure includes earthquake, tsunami, storm surge and wind engineering experimental facilities, computational modeling and simulation tools, research data and cyberinfrastructure, data collection tools and technologies, and extreme events research coordination.

Since NHERI was funded in February 2017, over 140 research projects funded by NSF and other entities have been completed. When coupled with education and community outreach led by the Network Coordination Office, NHERI advances research and educational efforts that contribute significant knowledge and innovation toward improving the resiliency of the nation's civil infrastructure to withstand natural hazards.

The 12 components of NHERI are highlighted on the next page. Appendix A includes examples of research campaigns, while Appendix B describes the capabilities of each of the NHERI components. More detail and resources are available on the DesignSafe website.[2]

1. *The Science Plan does not include other natural hazards such as fire, snow blizzards, drought, rock or mud slides. These are covered in other NSF programs.*
2. *https://www.designsafe-ci.org/facilities/nco/science-plan/*

Natural Hazards Engineering Research Infrastructure (NHERI).

The Science Plan Task Group guided the development of the first five-year NHERI Science Plan, which was first released in July of 2017.

The plan was generated with review and input from the NHERI facility leadership, the Network Coordination Office (NCO), and broad community-based participation of earthquake, wind, and coastal engineering professionals, social scientists, and engineering education experts.

The first edition of the plan was published via DesignSafe and widely distributed via email and newsletter campaigns. It was also highlighted during several professional meetings as a resource for the broader natural hazards engineering research community.

This 2020 edition of the Science Plan has been augmented with the input received during several key activities in NHERI, including:

- Reviews conducted during the NHERI Summer Institutes with early career researchers and practitioners in 2017, 2018, and 2019.
- Public comments received during the first three years of NHERI operations and responses from the authors of this 2020 version.
- Input received from the participants during the Science Plan Workshop held in Alexandria VA on March 18-19, 2019, summarized in the workshop final report[3].

3. *https://www.designsafe-ci.org/media/filer_public/cd/a5/cda5a60e-4ac5-4c77-a87a-0374ffee6645/2019_nheri_intl_workshop_report.docx*

Purpose

The NHERI Science Plan provides the earthquake, wind, and coastal hazards research community, including NSF and other funding agencies, a roadmap for high-impact, high-reward, hazards engineering and interdisciplinary research at NHERI facilities. The research results are intended to enable damage mitigation and prevent loss of life from natural hazards.

National Imperative for Resilience to Natural Hazards

Natural hazards in the form of earthquakes, windstorms, and associated events such as tsunami and storm surge can be devastating to the built environment of a community and highly disruptive to broader society. As evidenced by experiences from the recent Canterbury earthquakes in New Zealand, the Tohoku tsunami in Japan, the Joplin, Missouri, tornado and Hurricanes Katrina (U.S. Gulf Coast), Sandy (U.S. northeastern coast) and Maria (Puerto Rico), communities can take years to recover from widespread failures of, or damage to, civil infrastructure.

Disaster resilience is a national imperative. According to (FEMA 2018), "2017 was an unprecedented year in the wake of Hurricanes Harvey, Irma, Maria and the California wildfires, with more than 25 million people affected by these major disasters–almost 8 percent of the United States population."

Since 1980, the United States has been impacted by multiple large-scale disasters that have caused over a trillion dollars in economic losses (NOAA 2019 [4]). Hundreds of Americans have perished in these events, including disproportionate numbers of elderly, low-income, and racial minority individuals. Many thousands more have been displaced, some permanently, from their homes.

Federal expenditures for these disasters are borne by the entire country and have been growing steadily for the past 60 years. In 1953, for example, federal spending on disasters totaled $20.9 million (adjusted to 2009 dollars) or $0.13 per person.

NHERI RAPID: Training a Diverse Next Generation of Reconnaissance Researchers

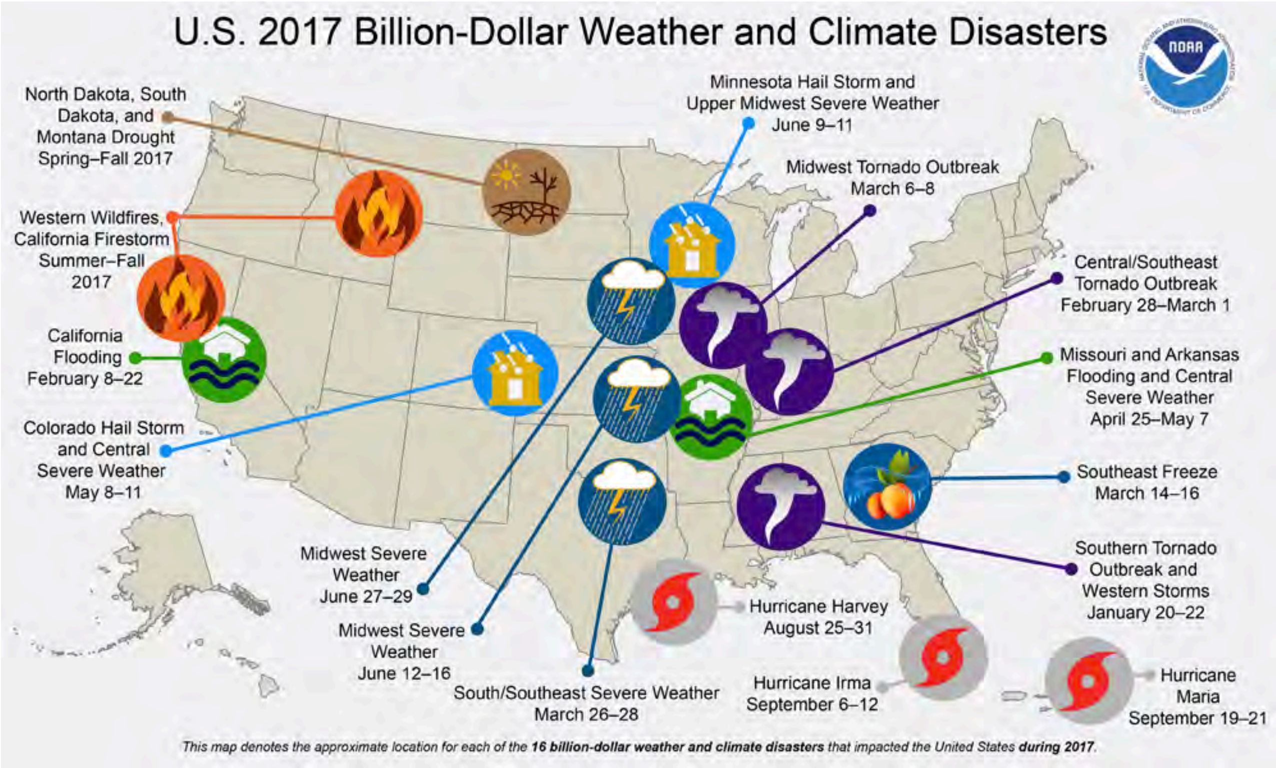
The NHERI RAPID facility is dedicated to advancing natural hazards reconnaissance through the shared use of equipment, tools, and technologies.

Since its founding in 2017, RAPID has conducted 18 training sessions for over 200 researchers from diverse disciplinary, geographic, and cultural backgrounds.

In 2009, with many more disaster declarations, the federal government spent $1.4 billion—about $4.75 per person—on disaster relief (National Research Council 2006[5]). This federal spending does not include the staggering costs of disasters to individuals as well as to cities, states, industry, and public infrastructure, only a portion of which is covered by insurance.

If the present course is continued, data suggest that the cost of disasters will continue to rise both in dollar amounts and in social, cultural, and environmental losses to communities.

4. *NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2019). https://www.ncdc.noaa.gov/billions/*
5. *https://www.nap.edu/catalog/11671/facing-hazards-and-disasters-understanding-human-dimensions*



2017 U.S. Billion-Dollar Weather and Climate Disasters: Historic Year in Context (Graphic: Climate.gov[6]).

The outcomes of this Science Plan, when fully realized by the NHERI community of researchers, engineers and other professionals, will provide a significant contribution through the implementation of new knowledge, technologies, and research capabilities to prevent natural hazard events from becoming disasters. This is a significant step towards reducing loss of life and expenditures caused by natural hazards of earthquake, windstorm, tsunami, coastal surge and waves.

Earthquake damage in Sendai Province Japan after the 2011 Tohoku Earthquake (Photo: Thomas Smith).

6. *https://www.climate.gov/news-features/blogs/beyond-data/2017-us-billion-dollar-weather-and-climate-disasters-historic-year*

Plan for NHERI

Until recently, engineering research on physical civil infrastructure materials, design, and performance has focused on resilience for a single natural hazard. Multi-hazard events are more common now and in populated areas civil infrastructure design must change to accommodate the rising threats that many communities face.

Such improvements in design will contribute toward broader societal goals such as protecting the safety and well-being of diverse populations and maintaining essential operations and services in natural hazard-prone regions.

With the establishment of NHERI, design of civil infrastructure is changing to address societal goals for a sustainable nation. Examples of sustainable strategies include the use of sustainable materials, minimization of non-renewable energy use, use of on-site renewable energy source(s), and maximization of material reuse and recyclable components.

However, current civil infrastructure designs do not always take advantage of new technologies for sustainable civil infrastructure and may not provide multi-hazard resilience. NHERI includes advancing computational modeling and simulation from component to system levels.

These advancements require computational simulations that are strongly supported by system-level response data from laboratory testing and post-event field observations. NHERI enables research and education that can contribute knowledge for sustainable and resilient civil infrastructure, throughout its lifespan.

The addition of the CONVERGE Facility to NHERI advances disciplinary and interdisciplinary hazards and disaster research. CONVERGE establishes and supports networks between research communities. An important part of CONVERGE's mission is to identify and coordinate social science and engineering researchers and interdisciplinary research teams before, during and after disasters.

Importantly, NHERI also will support one of NSF's core values associated with broadening opportunities and expanding participation of groups, institutions, and geographic regions that are underrepresented in science, technology, engineering, and mathematics (STEM).

NSF and NHERI are committed to this principle of diversity and have engaged students and early career researchers through the NSF Research Experience for Undergraduates program and the NHERI Summer Institutes.

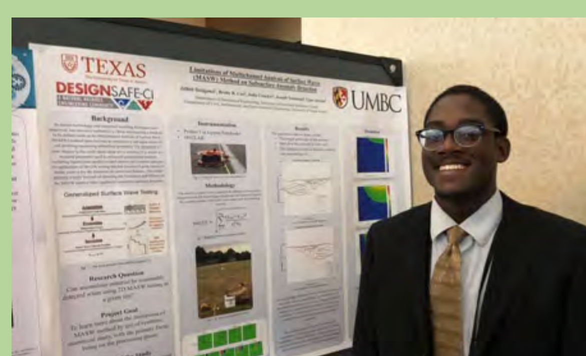
NHERI Summer Institute participants (Photo: Julio Ramirez).

NHERI Research Experiences for Undergraduates Prepare for Graduate School

The NHERI REU summer program provides faculty-mentored research experiences for undergraduate students across 10 NHERI experimental, reconnaissance, simulation, and cyberinfrastructure sites.

REU students attend online research meetings and career workshops. They present their research and research posters.

In three years, a total of 77 undergraduates from across the U.S. as well as Guam and Puerto Rico participated in the NHERI REU program. Demographics include: 31% first-generation college students, 56% female, and 42% underrepresented minority.



Process

NHERI seeks to foster ground-breaking research in the Grand Challenge areas. At the same time, NHERI will spur new ways of conducting research that are collaborative, multidisciplinary, and innovative. In addition, NHERI is focused on developing information and tools that can be implemented--either in the near term or the long term--in measurable, effective ways that will improve community resilience. To address this, the following approaches to NHERI research proposals are encouraged.

- Expanding "convergent" research is one of the 10 Big Ideas for Future NSF Investments (NSF 17-065). Convergence research moves beyond multi and interdisciplinary research to focus on boundary spanning activities designed to solve pressing environmental and social challenges. Convergent thinking and research is most effective in the context of diverse research teams that integrate across disciplines and accelerate the transfer of knowledge, theories, data, and research methods. Fresh voices can open new ways of thinking about old issues.

- Formulating proposals that focus on multiple hazards or that clarify how the research in one hazard could be beneficial in addressing other hazards.

- Including a time horizon for potential implementation. Some research might aim for developing information that can be implemented within a few years; other, more fundamental research might take longer to realize the full implications, and how it might best be used. Both horizons are encouraged, but identifying expectations for both cases helps improve efficacy.

- Where appropriate, including practitioners in research projects to provide advice on what specific elements of the research are needed, to help communicate research results, and to suggest how to implement results.

- Planning from the outset how the research can be incorporated into academic curricula and practice and what steps might be needed to accomplish the transfer. To assist researchers, NHERI has a Technology Transfer Committee as well as an Education Coordination Office.

Technology Transfer Committee contributes to design guidelines, technical briefs, seminars, building codes, and standards

An important measure for NHERI research is how the newly discovered knowledge impacts modern architectural and engineering practice and reduces vulnerability to earthquake, wind, tsunami, storm surge, and wave hazards.

NHERI addresses this challenge with the creation of a Technology Transfer Committee (TTC), a group of key volunteer experts and decision-makers who have influence to contribute to design guidelines, technical briefs, seminars, building codes, and standards.

TTC members identify completed research projects in natural hazards that are ready for implementation, and champion the research results for inclusion in widely accepted standardized documents that define the state-of-practice in a given architectural or engineering community.

The membership on the TTC is selected to address a multitude of key stakeholder communities, including those with expertise in earthquake, wind, geotechnical, and coastal engineering.

The TTC then works collaboratively with concrete/ masonry/ steel/wood construction, architecture, lifeline infrastructure, social sciences and policy, and standards development professionals to move knowledge into action.

Grand Challenge Subject Areas

The NHERI Five-Year Science Plan covers both the scope and the process of conducting multi-hazard research for improving civil infrastructure.

It is organized around three Grand Challenges with five Key Research Questions, which should help guide NHERI research.

For each of the Key Research Questions, high-priority research subject areas are also provided to assist future researchers in solving the Grand Challenges.

While the research plan is meant to provide guidance, it is also written in an open manner to ensure that the ingenuity and creativity of the broader community is fully encouraged.

Three Grand Challenges

1. Identify and quantify the characteristics of earthquake, windstorm, and associated hazards—including tsunamis, storm surge, and waves—that are damaging to civil infrastructure and disruptive to communities.

2. Assess the physical vulnerability of civil infrastructure and the social vulnerability of populations in communities exposed to earthquakes, windstorms, and associated hazards.

3. Create the technologies and engineering tools to design, construct, retrofit, and operate a multi-hazard resilient and sustainable infrastructure for the nation.

Social vulnerability often refers to both the pre- and post-event social and economic conditions of population groups within a given community or defined geographical space.

The most socially vulnerable groups tend to have the fewest economic and social resources to prepare for, respond to, and recover from a disaster.

In addition to being economically marginalized, these groups often tend to have less political power, fewer social networks, and less access to information. They also often live in neighborhoods and communities with decaying infrastructure and housing stock that is older and less likely built to modern standards. Thus, social vulnerability is often amplified by vulnerability of the civil infrastructure.

Terraformer for Boundary Layer Analysis at University of Florida NHERI Experimental Facility (Photo: Bernard Brezinski, University of Florida).

Key Research Questions

Five key NHERI research questions at the cusp of emerging transformative discoveries for earthquake, wind, and coastal hazards engineering are listed below.

1. How do researchers characterize the transient and variable nature of the loading actions imposed on the nation's civil infrastructure from earthquakes, windstorms, and associated hazards?

2. How can the scientific community enable robust simulation of the behavior of civil infrastructure to loading from earthquakes, windstorms, tsunamis and associated coastal hazards, while also considering the effects of these hazards on individuals, households, and communities?

3. What are the key physical responses, vulnerabilities, and factors influencing post-event recovery of civil infrastructure and communities?

4. What are effective and potentially transformative mitigation actions to achieve community resilience, especially when considering different hazards, shifting vulnerabilities, emerging technologies, and sustainability goals?

5. How can the scientific community more effectively collect and share data and information to enable and foster ethical, collaborative, and transformative research and outcomes?

The following subsections elaborate on each of these research questions.

Creating and capitalizing on forward- thinking technology are fundamental to the mission of the National Science Foundation and are essential to advancing the mission of the NHERI program.

Despite decades of advancements of our understanding of how civil infrastructure responds to earthquakes, extreme wind events, and coastal hazards, natural hazard-induced infrastructure damage and loss of community function continue to rise.

Technologies that advance or optimize the design, operation, and construction of civil infrastructure are sought.

Artificial intelligence and robotics are ripe areas for investigation. NHERI researchers should seek to leverage emerging trends giving rise to these developments.

Natori Beach seawall with large amount of scour and damage in the inland side of the seawall. Seaward face of seawall was intact (Photo: Lesley Ewing, courtesy of ASCE).

KEY RESEARCH QUESTION #1

How do researchers characterize the transient and variable nature of the loading actions imposed on the nation's civil infrastructure from earthquakes, windstorms, and associated hazards?

Loading actions are at the start of the design process. The large uncertainty of loading actions from natural hazards is particularly challenging for performance-based engineering. Reduction of the uncertainty would lead to more efficient and effective designs.

For example, research is necessary to:

1. Develop better approaches for laboratory testing to evaluate earthquake, tsunami, wind, surge and wave effects. Initially, this must be done in the context of existing facilities, but new and potentially transformative procedures, instrumentation, and facility improvements will be enabled in the NHERI program. Advanced testing will lead to superior numerical models with more realistic nonlinear and stochastic interactions that leverage NHERI cyberinfrastructure and computational and simulation components.

2. Develop methods to more realistically characterize wind, earthquake, tsunami, and storm surge and wave loading on buildings and other structures. The highly simplified models of loading effects used in engineering practice can dramatically over- or under-estimate the loading effects, especially on components and subsystems. Examples include tornado effects on buildings and other structures, concentrated wind loading effects on building components and cladding, water and waterborne debris loads on built structures, and soil-structure interaction under spatially incoherent earthquake ground motions. Advanced numerical simulation methods based on high-fidelity computational models should be verified based on data obtained from laboratory experiments and field measurements and observations.

3. Improve our ability to connect frequency and intensity geospatial hazard data to site-specific loading actions on geomaterials, geostructures, buildings (including non-structural components), and other structures. The earthquake, wind, geotechnical, structural and coastal engineering communities are working with seismologists and atmospheric scientists to develop broad hazard data; but site-specific effects such as path-of-travel, site geomaterials, and local surface environment can heavily influence loading actions.

NHERI CONVERGE: Coordinating Rapid Reconnaissance Researchers

How will the research community respond effectively in the event of a major disaster?

NHERI CONVERGE is home to the first-ever disaster reconnaissance Leadership Corps—which includes the leaders of the NSF-funded Extreme Events Research / Reconnaissance networks and the NHERI components that support them.

The Leadership Corps is working together to ensure that geotechnical, social science, structural engineering, coastal, operations and systems engineering, and interdisciplinary research communities are effectively coordinating, communicating, and collaborating as they do scientifically rigorous and ethically grounded work.

KEY RESEARCH QUESTION #2

How can the scientific community enable robust simulation of the behavior of civil infrastructure to loading from earthquakes, windstorms, tsunamis and associated coastal hazards, while also considering the effects of these hazards on individuals, households, and communities?

Development of improved end-to-end simulation overlaps with Key Research Question #1 and brings to the forefront the importance of a coordinated approach between researchers and NHERI.

However, improvements for simulating loading actions should be done in the larger context of predicting structural and non-structural responses such as vegetative or zoning measures.

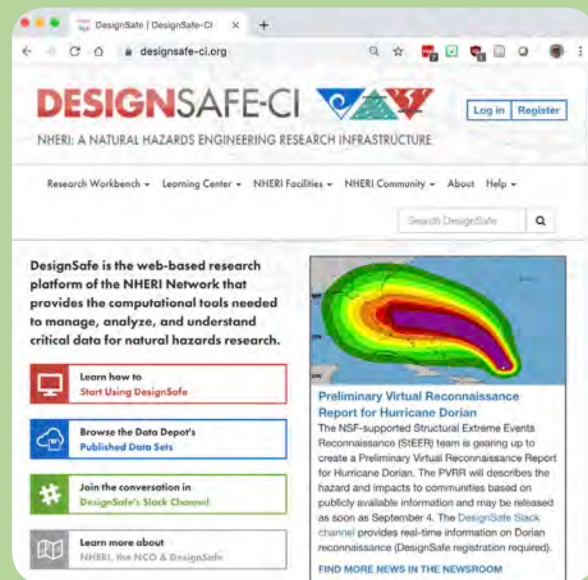
For example, research is necessary to:

1. Improve methods for simulating earthquakes, windstorms, tsunami, storm surge and wave loading actions as well as ground, geostructural, structural, non-structural, and building envelope response — for the purpose of establishing physics-based, end-to-end models.

2. Improve simulation of regional effects and response, including interrelated and system effects as well as response and recovery decisions.

3. Improve numerical methods to simulate detailed response of above- and below-water geostructures, structures, and other building components as alternates or adjuncts to physical testing.

4. Improve design methods to capture the more complex behavior that occurs under actual loading from natural hazard conditions.



NHERI DesignSafe Cyberinfrastructure: Enabling Research Through Data, Analytics, and Computation

DesignSafe is a web-based research platform that provides cloud-based tools to manage, analyze, understand, and publish critical data for natural hazards research.

Replacement of eastern span of San Francisco-Oakland Bay Bridge following failure of the existing bridge from the 1989 Loma Prieta Earthquake, 2013 (Photo: licensed by © Frank Schulenburg / CC BY-SA 3.0).

KEY RESEARCH QUESTION #3

What are the key physical responses, vulnerabilities, and factors influencing post-event recovery of civil infrastructure and communities?

Public bath house near the shoreline of Arahama Beach, Sendai, showing 4m of scour from tsunami (Photo: Lesley Ewing courtesy of American Society of Civil Engineers).

Characterizing response and performance of buildings and other structures using "vulnerability" enables identification of threats to resilience and prioritization of research thrusts.

For example, research is necessary to:

1. Identify vulnerability indicators and metrics to be employed in resiliency analyses. Vulnerability is used here in both the physical sense of the built environment as well as in the social sense of the well-being of community inhabitants.

2. Systematically investigate interrelationships of components in systems to identify key vulnerabilities affecting resilience at all levels.

3. Systematically investigate civil infrastructure and community interrelationships to identify the most efficient balance between improved mitigation and improved response and recovery.

4. Enhance performance-based design procedures for tsunami, storm surge and waves, and wind effects parallel to those available for earthquakes, particularly considering debris impact and performance of the building envelope. These procedures should enable economical designs for improved performance, and life-cycle analysis with defined uncertainty. Eventually, these procedures should be integrated to produce consistent multi-hazard analysis.

5. Improve system and component fragilities for use in performance-based design and loss estimation.

KEY RESEARCH QUESTION #4

What are effective and potentially transformative mitigation actions to achieve community resilience, especially when considering different hazards, shifting vulnerabilities, emerging technologies, and sustainability goals?

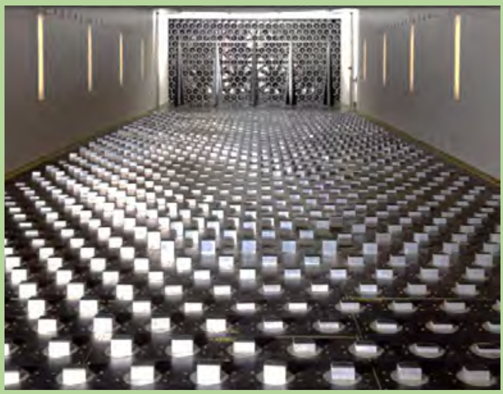
Few, if any, communities assess themselves as being adequately resilient for all natural hazards. For example, research is necessary to:

1. Develop sensor systems that can measure changes in civil infrastructure vulnerability due to age or hazard loading from component to system level, including inaccessible structures such as buried pipelines. Identifying increased vulnerability of infrastructure is necessary to maintain resilience, particularly in promoting mitigation actions and in post-event response and recovery.
2. Understand spatiotemporal variation in wind, surge, wave, and related erosion and debris during coastal storms in order to better characterize and predict infrastructure impacts. Develop sensors and sensor systems that can improve the prediction of formation and motion of windstorm systems such as hurricanes and tornadoes.
3. Identify, test and develop new strategies and materials to mitigate the impact of earthquakes, windstorms and related natural hazards of tsunami and storm surge and waves on civil infrastructure and to identify life-cycle benefits of improving performance for existing infrastructure.
4. Develop best practices for design and construction of geotechnical, structural, and non-structural systems, including use of new materials for the most common model building types (e.g., structural material, occupancy, and size) and non-building elements used in the U.S. considering cost, multi-hazard performance, and sustainability.
5. Develop methods to consider life-cycle performance under earthquakes, windstorms, and related natural hazards of tsunamis, storm surges and waves. These methods need to be incorporated into performance-based design procedures.
6. Identify and develop improvements to the sustainability benefits of proposed enhanced performance under hazard loading to infrastructure components and systems as well as enhanced resilience of communities.
7. Develop approaches by which the characteristics of natural geomaterials can be enhanced either alone or in concert with other components using natural and/or human inspired and/or mediated techniques so that their performance during extreme loading events is enhanced.

NHERI Boundary Layer Wind Tunnel Shared Use Facility: Improving Wind Hazard Resilience

The Boundary Layer Wind Tunnel at the University of Florida offers unique automation and flow-control capabilities that facilitate rapid experimental execution over a broad spectrum of wind hazards.

This state-of-the-art shared use facility has enabled researchers across the nation to break new ground in wind hazard research. For example, real-time optimization of structural performance under wind loads has been achieved by combining articulating models with cyber-physical simulations. These NHERI collaborations are advancing the basic science needed to create resilient communities.



UFLORIDA NHERI
Powell Family Structures and Materials Laboratory

KEY RESEARCH QUESTION #5

How can the scientific community collect and share data and information to enable and foster ethical, collaborative, and transformative research and outcomes?

Field observations and analyses are key to providing the data and information that is required to evaluate both experimental and numerical studies. These observations can reveal information that overlaps several disciplines and may stimulate integrative studies.

For example, research is necessary to:

1. Improve availability of quality inventories of site conditions and civil infrastructure for use in research studies. Such partial or complete inventories can help identify threats to community resiliency and prioritize research on the civil infrastructure components.

2. Develop regional systems to collect and analyze sensor and image information for use in planning, mitigation, response, and recovery.

3. Develop instrumentation and measurement systems that, in documenting damage, can create 3-D images of the facility or structures in the pre-event condition, which will allow analysis to further understand the event that caused the damage—often well after the event has passed.

4. Develop cyberinfrastructure to collect, store, and analyze field data from hazard events using a data repository in a format amenable to use by a wide variety of users. The DesignSafe cyberinfrastructure, which holds data collected by researchers using tools from the RAPID facility and NHERI projects, should give researchers the ability to study hazard-event data at a more granular level than ever before.

In the NHERI plan, all natural-hazard field damage data can be stored on DesignSafe and be accessible to anyone. This is a much-needed resource for the earthquake, wind, tsunami, storm surge and wave communities, because no other centralized system is in place for archiving their post-event observations.

NHERI Summer Institute Teams Collaborate on Ideas for NSF Proposals

Each year, NHERI awards approximately 20 travel grants for early career faculty and senior-level graduate students to attend the Summer Institute. The 3-day workshop presents NHERI resources, NSF grant writing tips, and a CAREER workshop and panel, along with many networking opportunities. As of August 2019, 23% of NHERI Summer Institute alumni successfully secured grant funding for their research.

Vessel thrown ashore by tsunami created from nearshore earthquake in Chile, 2010 (Photo: Billy Edge).

Opportunities for Disruptive and Transformative Research

The research needs identified by each Experimental Facility, as well as the SimCenter, DesignSafe, CONVERGE and the NCO are not intended to be constraining but rather to encourage use of the unique NHERI research infrastructure in innovative ways.

Research ideas are encouraged that can, for example, advance multi-hazards research that addresses cascading disasters and associated failures; develop and test new materials as well as structural and non-structural systems; explore novel use of disruptive technologies; foster the creation of interdisciplinary teams for projects requiring the use of multiple experimental facilities; transfer experience, knowledge, and data from one hazard community to another, and use high-performance computing and simulation tools to advance understanding. These research ideas will lead to new discoveries in civil infrastructure performance in natural hazards.

Traditional and innovative uses of the NHERI facilities are currently being discussed and defined in workshops at various Experimental Facilities and will also be emphasized at each Summer Institute and at national and international NHERI workshops.

Significant and substantive advances has been made through disruptive technologies. The NHERI community in its Science Plan looks for opportunities to provide a platform to incorporate disruptive technologies that can significantly influence the design, operation, repair and resilience of civil infrastructure under natural hazards.

NHERI has sought ways to identify the contributions from disruptive and transformational technologies to the NHERI Science Plan to achieve the vision of NHERI. Some technologies and developments that have great promise at this time include:

NHERI Wall of Wind: Shared Use for a Safer Nation

The Wall of Wind at Florida International University is the nation's largest, most powerful university-based wind testing facility.

Under the NHERI umbrella, it is now open to researchers across the nation. Why does this matter? In 2018, Elaina Sutley, an assistant professor of civil engineering at the University of Kansas, was able to use test-based data generated by the facility to evaluate the performance of elevated houses and mobile home structures in major wind events.

This work would not have been possible at her home university, but now she is able to collaborate through NHERI to help advance community resilience through advancing new mitigation techniques for vulnerable structures.

The 12-fan Wall of Wind at Florida International University will enable better engineering against tornadoes, hurricanes and other windstorms.

- Advanced computational methods and high-performance and real-time computing
- Data-driven science
- Robotics
- Bio-inspired engineering design
- Additive manufacturing
- Advanced materials
- Convergence science
- Science of team science

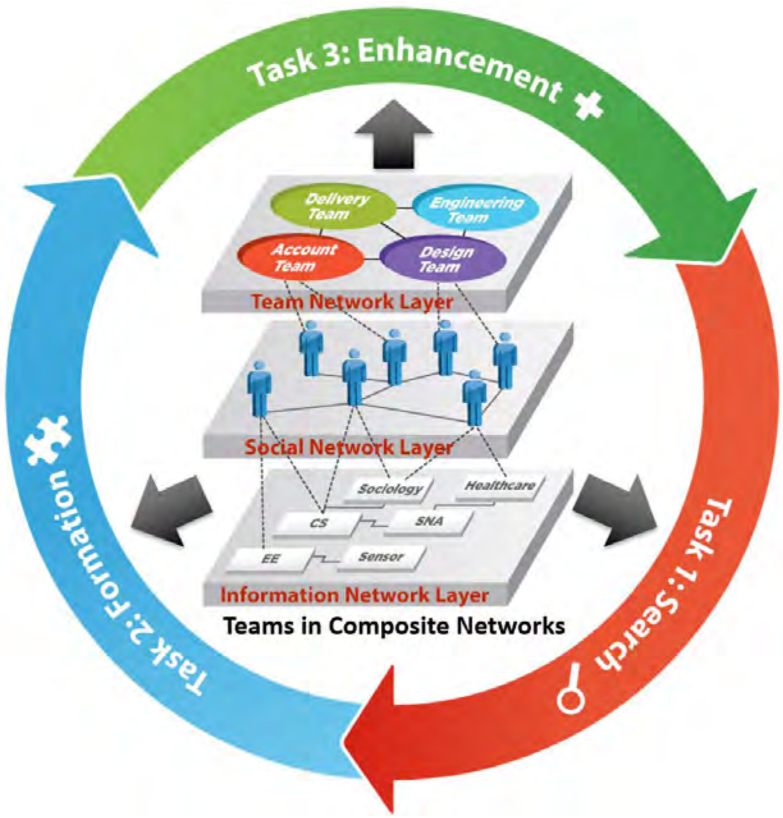
In forming teams to create substantive research outcomes, it is critical that researchers explore the science of team science. This is a relatively new interdisciplinary field that empirically examines the processes by which large and small scientific teams, research centers and institutions organize, communicate and conduct research. Moving into large research campaigns, the science of team science becomes more critical.

The vision for social and cognitive networks (SCN) is an ability to predict emergent phenomena in teams, organizations, and populations by creating new measures, models, and theories that capture behavioral and cognitive processes of groups.

Team science, computational social science, and social network analytics are important in achieving this vision. Creating a more resilient and sustainable human infrastructure will involve transforming traditional problem-solving by incorporating science of team science and social sciences with traditional engineering and science to create more resilient and sustainable human infrastructure.

The NSF Center for Bio-mediated and Bio-inspired Geotechnics at Arizona State University is focusing on opportunities to integrate geotechnical engineering with bio-mediated processes that are managed and controlled through living biological activity.

These efforts include bio-inspired processes together with biological principles employed to develop new abiotic solutions with no living organisms. Sustainable and resilient geotechnical systems can be built mimicking nature, which has developed many elegant and efficient bio-geotechnical processes over millennia that have the capability to provide resilience to communities exposed to wind storms, tsunamis and storm surge.



Design of High-Performance Teams (Source: Personal Communication Hanghang Tong, University of Illinois).

Robotics presents another opportunity to advance NHERI through several applications.

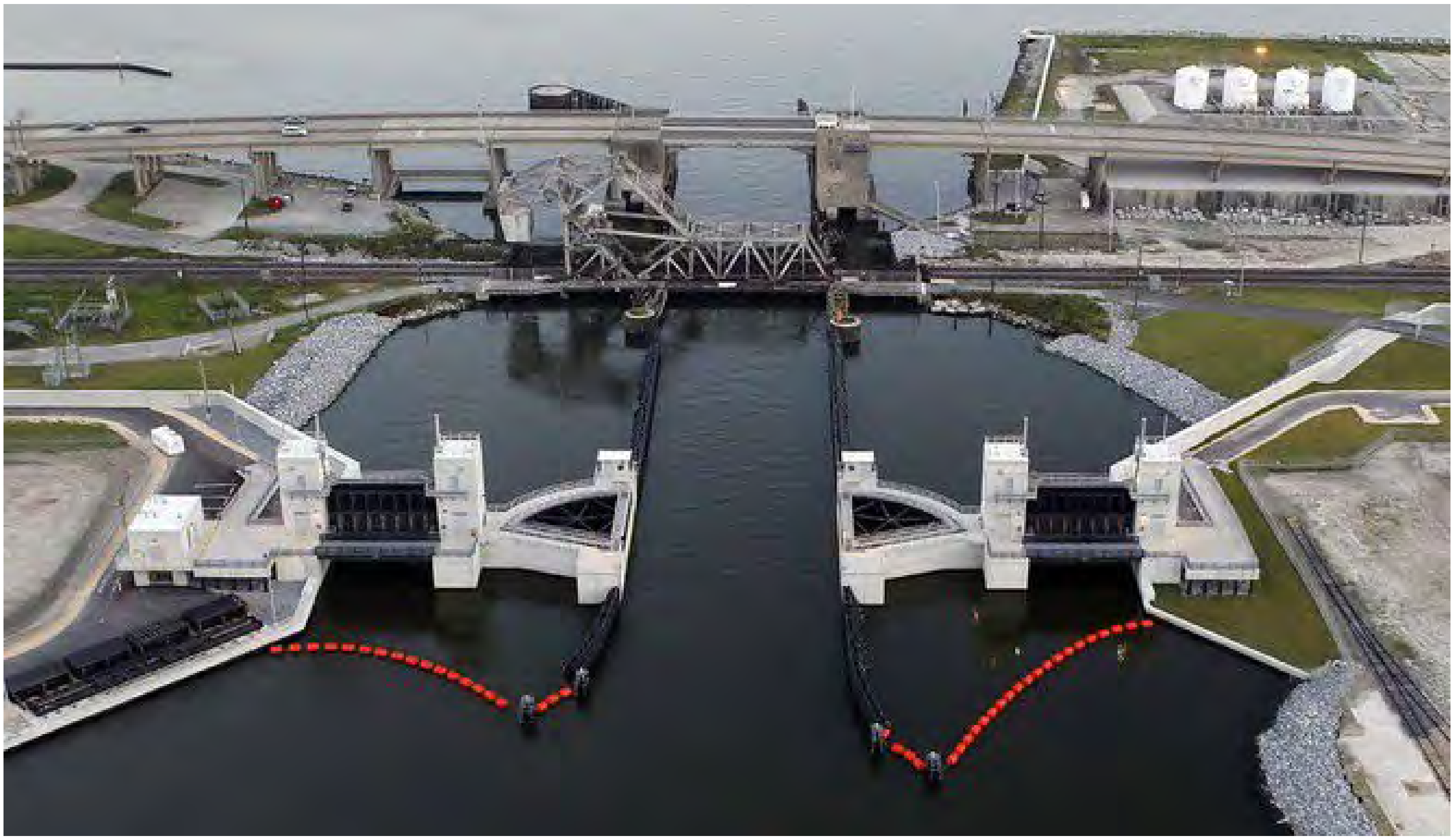
One such application could be deploying self-burrowing robots that could determine soil properties, physical and chemical, prior to rebuilding in hazard areas. Robotics could be used to investigate by navigating inside hazardous cave-like areas or lava tubes using advancements in positioning and location controls.

For research to make significant steps forward, it is important to look to research campaigns encompassing one or more of the hazards under the scope of NHERI.

These campaigns allow the opportunities to bring together traditional approaches with disruptive technologies and aspects of social science. Examples of five specific research campaigns are included in Appendix A of this document.

Included are examples from (i) Earthquake and Related Landslides; (ii) Windstorm Hazards; and (iii) Storm Surge and Tsunami Hazards. Each of the campaigns described includes a Research Challenge, a statement of Intellectual Merit, and a discussion of Broader Impacts.

Tornado damage of School in Greensburg, Kansas, 2007 (Photo: Thomas Lee Smith).


New Orleans Inner Harbor Navigation Control Seabrook Floodgate Complex (Photo: U.S. Army Corps of Engineers).

Concluding Remarks

The NHERI Five-Year Science Plan provides information for constituents, including practitioners, as well as guidance for members of the research community.

The sense of purpose, combined with ethics and ingenuity, are among the community's greatest assets, so this document is not intended to constrain or limit ideas, but rather to both identify high value research needs and spark development of meaningful research proposals.

This Science Plan is meant to serve as a living document—one that will continue to be reviewed and updated to reflect new funding streams, projects, challenges as well as new scientific breakthroughs and opportunities for further exploration.

Thus, the ongoing quality and usability of this document is contingent on community input and feedback from NHERI researchers. Various architectural, engineering, and scientific outputs will continue to be shared with members of the research, practice, and policy communities that can most benefit from learning of the ongoing progress.

NHERI facilities are organized to build on prior scientific breakthroughs and successes, while looking toward the future for the next transformative ideas that will ultimately help save lives and reduce the damage and dollars lost associated with disastrous events.

The Science Plan will be widely disseminated via the NHERI DesignSafe Cyberinfrastructure to researchers and practitioners in the natural hazards community and to the National Science Foundation. In addition, this updated plan will be shared through workshops, and professional meetings and with the international community.

Hurricane Ike wind and wave damage on Galveston Island (Photo: Billy Edge).

Ultimately, this plan is designed to spark new ideas and to facilitate use of the NHERI components, all with a vision of a safer built environment and a reduction in the harm and suffering caused by earthquakes, windstorms, tsunamis, and coastal storms.

Earthquake damage in Bingöl, Turkey (Photo: Antonio Bobet).

APPENDIX A:
EXAMPLE RESEARCH CAMPAIGNS

Appendix A: Example Research Campaigns

INTRODUCTION

As part of the 2019 NHERI International Workshop to Develop Research Campaigns, Interdisciplinary Teams, and Disruptive Technologies for the NHERI 5-Year Science Plan for Natural Hazards Engineering Research, all participants were invited to take part in an interactive breakout session where they completed a draft template for a research campaign.

The template included below was constructed to ensure that the scope of each of the campaigns would be aligned with the National Science Foundation review criteria, with an emphasis on intellectual merit and broader impacts.

The members of the Workshop Organizing Committee created a series of questions that were included in the template, with an eye toward ensuring interdisciplinary work. In particular, the questions were meant to capture issues and concerns that are integral to engineering, the social sciences and public policy applications.

Campaign scope:

- What is the problem, challenge or issue that your group is addressing?
- What is the intellectual merit?
- What is the intended broader impact?

In developing your research campaign, please consider answering all or relevant questions from below:

- What is the timeline to accomplish the multiple objectives to reach the goal of the research campaign?
- How will you incorporate disruptive technologies?
- Which of the NHERI facilities can be used – how will the facilities be utilized?
- What multi-disciplinary teams will be represented?
- How will you include underrepresented groups?
- What is the socio-demographic makeup of the place where your campaign will focus? What justice or equity issues may need to be considered?
- Can you describe your campaign in a hazard scenario/ geography/multi-hazard context?
- What are the known or unknown characteristics of the natural hazard?

Participants chose and participated in one of the three breakout sessions on the second day of the workshop. Those sessions focused on 1) earthquakes and landslides; 2) wind events; and 3) tsunamis and other coastal hazards.

Some sessions broke further into subgroups to focus on different topics. The groups in each session then had approximately two hours to identify a problem or concern and to complete the template for the research campaign.

The questions on the template were meant to serve as guideposts to ensure that all team members would think from a multi-disciplinary perspective, would consider team formation dynamics, and would focus on how they would select and use NHERI facilities to advance their campaign.

The outcomes of each of the breakout themes are given below to describe Research Challenge, Intellectual Merit and Broader Impact.

The parapet toppled on to an outdoor seating area. Fortunately, the earthquake occurred at 4:45 am. The most dangerous building type is the older unreinforced masonry bearing wall building, still common in regions of high seismicity (Photo: Bill Holmes).

Appendix A1: Resilience of Lifeline Systems

RESEARCH CHALLENGE

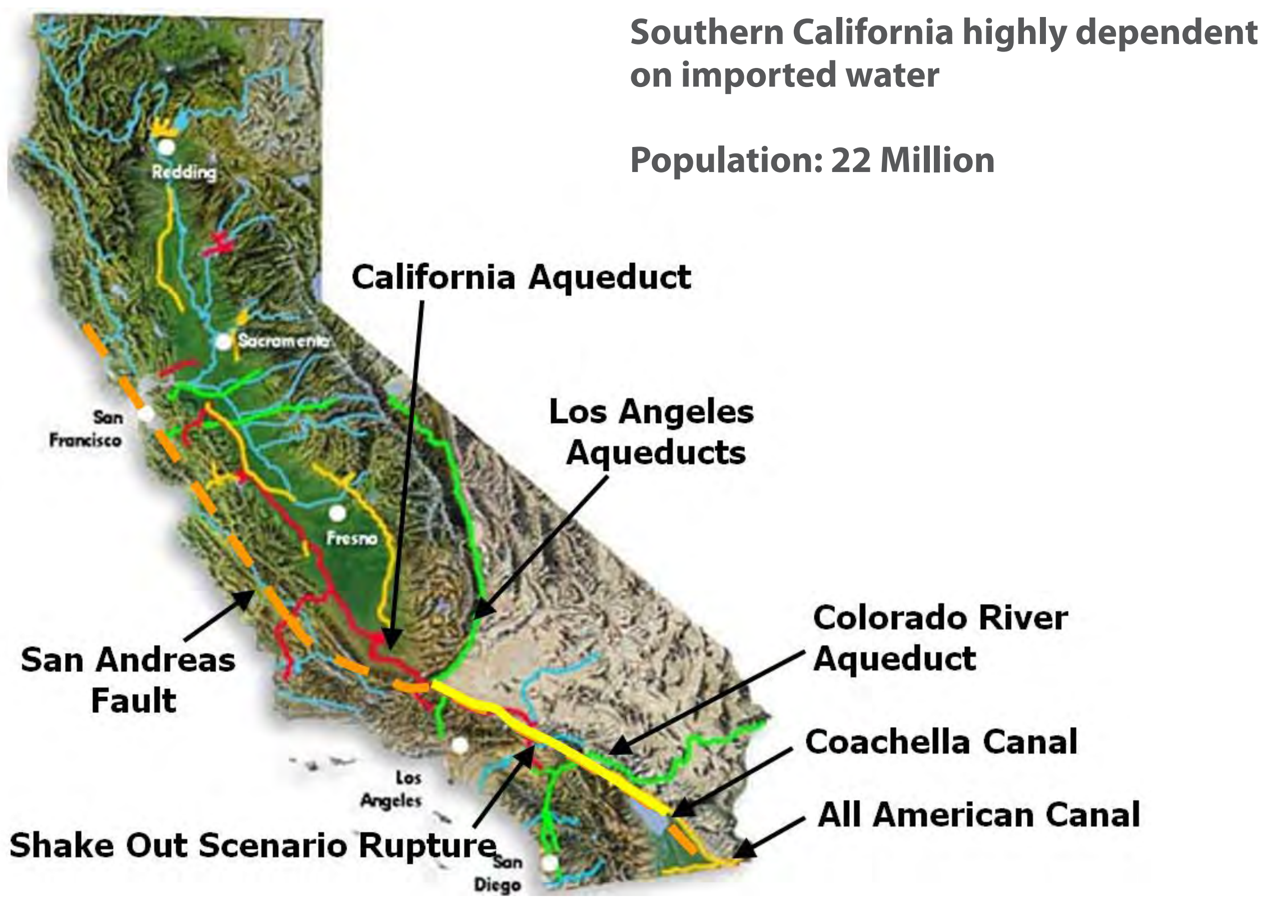
Lifeline systems are key infrastructure elements that support communities. Failure of such systems can prevent people from returning to their homes and cause businesses to relocate after a natural hazard event.

Lifelines are vulnerable to natural hazards such as flooding and earthquakes. Recent events such as the Kobe earthquake in 1995, the 2005 Hurricane Katrina and the 2017 Hurricane Maria caused widespread damage to lifeline systems and serious disruption to the economy and social fabric of the communities affected. The water distribution system is one of the most important lifeline systems, and existing infrastructure is known to be vulnerable to natural hazards.

There are more than 7,000 km of cast-iron main water pipes in Los Angeles. Their level of performance and vulnerability against a natural hazard event is unknown, but their performance in strong ground-shaking from earthquakes is thought to be poor.

What is needed is to develop the science and engineering tools to identify the weaknesses in the system, to replace or upgrade the components so the network can perform at the level expected, and to develop strategies to ensure that the system is resilient and recovers quickly after damage or failure.

The problems that all lifeline networks have are similar. Thus, lessons learned and solutions proposed for one of the networks, e.g. water, can be used for others such as power, gas and waste systems.



Protecting Water Supplies (Graphic: Tom O'Rourke, Cornell University, closing presentation at the NHERI Science Plan Workshop, March 19, 2019, Alexandria Virginia)[7].

7. https://www.designsafe-ci.org/data/browser/public/designsafe.storage.published/PRJ-2300

There are also interdependencies between lifelines that also must be understood—such as the delivery of water that is often dependent on the availability of power. The research will address the following key questions:

1. What are the complex interactions between lifelines and how should we define these interactions among systems and within the community?
2. How should we assess the current performance of the elements of the system?
3. How should we assess network reliability and perform network analysis such that the weak elements of the system are identified?
4. What are the best and optimum strategies to replace or repair elements in the system?
5. What is the best strategy for recovery once the system is damaged?
6. What are the short-term and long-term environmental impacts of any retrofit, upgrade or replacement?

INTELLECTUAL MERIT

The proposed research will contribute to the resilience of lifeline systems and make the infrastructure of the nation more resilient against natural hazards. More specifically, the proposed research will:

1. Provide new knowledge and tools for network analysis and damage estimation.
2. Determine the interplay between lifelines and buildings and between humans and systems.
3. Quantify the interaction between ground response and lifelines.
4. Create new scalable models to simulate the response of the systems both at the element level and at the network level.

The following disruptive technologies have high potential to advance this research: new methods and new materials for ground improvement; robotics to evaluate and repair elements of the network; additive manufacturing for repair and retrofit; sensors and sensing for real-time monitoring of the network performance; big data and artificial intelligence for asset management; 3D imaging to characterize the subsurface; real time hybrid simulation and high-fidelity network analysis to model the network.

BROADER IMPACTS

The loss of lifelines, e.g. water, power, etc., disrupts gravely the communities affected, as has been the case in Puerto Rico, after Hurricane Maria, and as observed by the power loss in Venezuela.

Liquefaction in the Kaiapoi residential area from the 2010 Darfield Earthquake, New Zealand, caused significant damage to underground utilities preventing reoccupancy. This street sign was dropped about six feet straight down (Photo: Bill Holmes).

LIfeline disruptions cause economic and personal losses that disproportionally affect minorities and populations in the lower economic strata of society. Improvements in the resilience of lifelines will have a very large and positive impact across all members of society, especially those less-favored economically.

The results of the research can influence policy and/or be used by policymakers to prioritize operations and to choose the best financial mechanisms.

The research is highly interdisciplinary, as it needs to bring together expertise from different communities, that in a very broad sense, include:

1. Imaging, to characterize the system and its spatial variability.
2. Decision-support analysis, to develop new strategies for replacement, improvement or retrofit.
3. Social sciences, to involve the community in the decision-making process.
4. Communication, to bring the research findings to all stakeholders.

Appendix A2: Immediate Occupancy of Low-Rise Buildings Following Windstorms

Storm surge, Hurricane Ike, Boliver Island Texas, 2008 (Photo: Spencer Rogers).

RESEARCH CHALLENGE

Enable immediate occupancy of low-rise buildings (including residential, commercial, and critical facilities such as schools and hospitals) impacted by hurricane winds, rain, and storm surge.

This campaign includes future and existing buildings located in coastal as well as inland communities. It will address economic and cultural viability of solutions, recognizing the incredible socio-economic diversity of affected communities.

INTELLECTUAL MERIT

The goal is to develop the knowledge base and tools needed to allow viable retrofits of existing buildings, and design and construction of new buildings, including the following competencies:

1. Identify uncertainties in wind and wind-driven rain loading, and system resistance to determine where to focus research.

2. Develop innovative techniques for measurement of storm surge and wave effects during hurricane landfall.

3. Improve characterization of the coastal flooding hazard so as to reduce the potential for underestimation of future flood levels during design of elevated structures.

4. Advance research that enables design and installation of ventilation, door and window systems that prevent water entry.

5. Develop interdisciplinary engineering field diagnostic tools to assess existing building vulnerabilities while also including social science instruments that capture the socio-demographic characteristics of occupants.

6. Refine the understanding of wind-borne debris (e.g., extent of the wind-borne debris region, design momentum, rain resistance after debris impact, applicability to elements in addition to glazing).

7. Develop engineered and natural defense strategies to reduce localized wind loads, storm surge and wave action.

8. Further develop computational fluid dynamics (CFD) with the aim of using it to develop wind and storm surge loads, and augment assessment of building envelope resistance (currently determined by testing).

9. Develop behavioral nudge strategy to facilitate implementation of individual and community-wide resilience through mitigation.

10. Carefully consider economic barriers to adoption of particular mitigation strategies at the individual household as well as community level. Develop a range of policy options to address economic and social inequalities that may delay adoption.

BROADER IMPACTS

With significant projected population increases in hurricane-prone regions in the next few decades, and the potential ramifications of climate change, a notable improvement in the number of buildings in a community that can be immediately occupied after a hurricane will have a profound impact on the health and overall quality of life for millions of U.S. residents.

Although there have been significant improvements in design and construction of low-rise buildings since Hurricane Andrew devastated parts of Florida in 1992, recent hurricanes have caused billions of dollars in damages to communities and widespread disruption and dislocation because relatively few buildings have been suitable for immediate occupancy.

Prolonged building disruption presents significant economic, social, and mental health challenges to inhabitants of communities and negatively impacts a community's ability to rapidly recover. Clearly, a fundamental change to the current situation is needed to lessen the impact of more frequent and large-scale disasters on communities.

RESEARCH CAMPAIGN STRATEGY

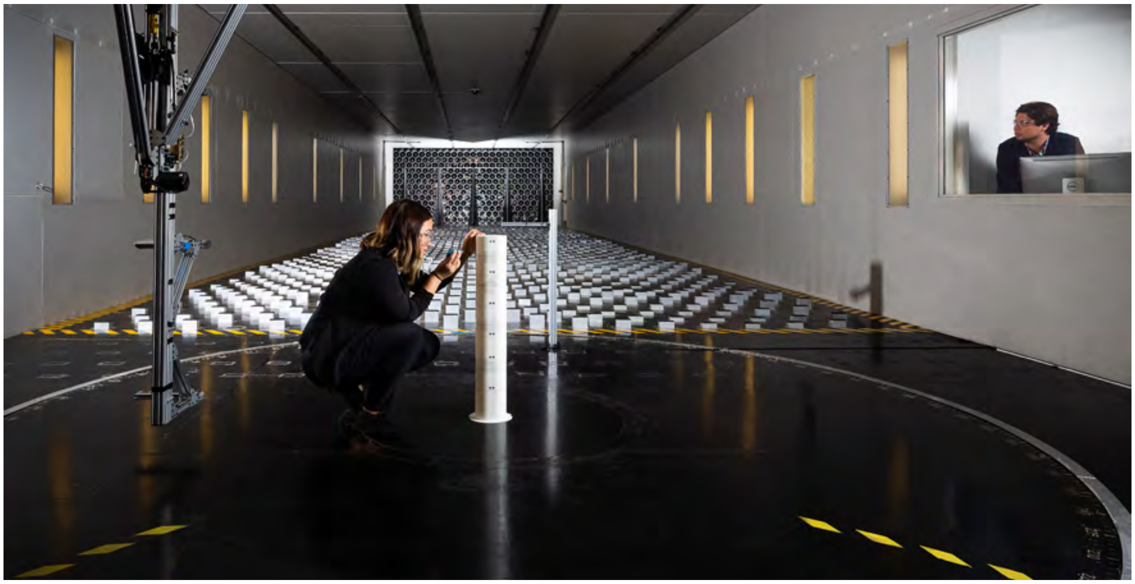
1. Submit a planning grant.

2. Use the Science of Team Science to identify team members, which could include representatives from, for example, public policy, sociology, demography, economics, engineering, architecture, building science, and construction management. Given the present and growing diversity of the coastal and inland areas, every effort will be made to include scholars from Historically Black Colleges and Universities (HBCU's) and Hispanic Serving Institutions. In addition, to ensure broader applications, the team will also invite private sector representatives who can assist with future workforce training opportunities.

3. Explore disruptive technologies that can be utilized in the research campaign.

4. Use the following NHERI facilities: CONVERGE, FIU Wall of Wind, RAPID, SimCenter, and U of Florida Wind Facility.

5. Timeline: Some research results will move into practice in the near-term (5 to 10 years). Other research results will be long-term (greater than 10 years).



Wind force measurements at at University of Florida NHERI Experimental Facility (Photo: Forrest Masters, University of Florida).

Appendix A3: Mega-Disasters

RESEARCH CHALLENGE

We want to shift the focus from chronic storms (hurricanes/tornadoes) to very acute thinking in terms of mega-disasters (e.g., atmospheric rivers), which involve a multi-state shock and are highly unpredictable by nature, taking lifeline systems offline and completely collapsing state governments.

In order for the country to be resilient to such a mega-disaster[8], this research campaign proposes to establish programs, build trans-disciplinary, inter-agency, and international collaborations, and perform fundamental research in operational settings, using all existing NHERI facilities, as well as potentially extending or developing additional facilities specific to the hazard characteristics.

The immediate focus of the proposed research campaign will result in a five-year timeline, with a need to re-assess at the end of the five years.

The programs developed will initially focus on:

1. Characterization of the hazard and loads.
2. Prioritization of infrastructure or improved structural performance.
3. Creating an idealized recovery plan for execution in the event of the mega-disaster.

A goal of the research campaign is to enable communities to be better prepared for extreme hazard events, as well as to generate the knowledge to build back in a more sustainable, efficient, and resilient manner, at 20% of the current social and economic cost.

INTELLECTUAL MERIT

The success of this research campaign will result in an efficient recovery plan that utilizes disruptive technologies, such as artificial intelligence, robotics, bio-inspired design, additive manufacturing, and advanced materials.

The recovery plan will rely on hyper-redundancies to provide efficient and effective response after the disaster event. New science will be generated on:

1. Rapidly deployable, pre-fabricated sheltering and rebuilding strategies.
2. Artificially intelligent-optimization of building designs and standards.
3. High through-put experimental (design-build-test) research.

An aerial view of the devastation in the Bahamas following Hurricane Dorian, 2019 (Photo: Brandon Clements ADAR/LSM).

8. Mega-Disaster is identified by the National Center for Disaster Preparedness as an event requiring a focus from policymakers and media attention on the likelihood of multiple cascading system failures and resulting injuries and deaths from large-scale events such as Hurricane Katrina or radiological emergencies.

London Avenue Breach in New Orleans near Lake Pontchartrain from Hurricane Katrina after Temporary Levee Reconstruction, 2005 (Photo: Billy Edge)

BROADER IMPACTS

This research campaign will organize workshops with individuals from different disciplines, utilizing science-of-team-science strategies to sustain a convergence program on mega-disasters.

The research campaign will integrate fundamental research into operation through inter-agency coordination (e.g., NASA, DOE, DOD, etc.) and will engage the public such that responsibility is shared across all community members from the local to federal level.

To address this challenge, a diverse team with representation from under-represented groups will be necessary.

The campaign will also focus on educating the public, not only on the detrimental effects of such a disaster, but also on the response and recovery processes which will be executed in the event of such a disaster, where in this type of event, key researchers and public officials may not be available to carry out proper procedures.

Appendix A4: Community-Level Management of Storm Surge and Tsunami Hazards

RESEARCH CHALLENGE

We envision a research campaign to develop the scientific and engineering knowledge needed to create the next generation of decision-support technologies for systems-of-systems-based[9], community-level management of vulnerabilities associated with storm surge and tsunami hazards.

The goal is to generate actionable knowledge and tools to inform values-based coastal planning over a 30- to 50-year time horizon and to incorporate long-term adaptation and risk management into the disaster recovery phase.

Through computational modeling, and laboratory and field experiments, we will explore how the engineered design of sociotechnical systems should change in response to different planning regimes focused on maintaining the resilience and sustainability of coastal communities.

Projects would include coordinated efforts between multiple NHERI facilities spanning wave and wind experimental facilities, along with the SimCenter and RAPID.

Another key element of this campaign is transdisciplinary engagement with local decision-makers and stakeholders in a diverse set of city/community-level test beds.

Experiments might include a mix of individual and integrated studies of elements at multiple scales (e.g., materials, components, buildings, public infrastructure). In addition, studies still need to quantify uncertainty associated with engineering performance of natural and nature-based features.

Regardless of scale, they should be motivated by how findings would enable better decision-making using contemporary approaches for decision-making under deep uncertainty (e.g., dynamic adaptive policy pathways, multi-objective robust decision-making).

Examples of these contributions include development of decision-relevant, community-level metrics; uncertainty quantification; and joint probability analysis of surge and wind hazards.

Directional Wave Basin (3D) at the NHERI@OSU Facility (Photo: Dan Cox).

9. System of systems is a collection of effective working task-oriented systems which when working together create a greater system.

San Francisco Oakland Bay Bridge looking west following the Loma Prieta earthquake. This shows the failed 15-m long section at Pier E-9 (Photo: E.V. Leyendecker, U.S. Geological Survey).

INTELLECTUAL MERIT

Research projects are encouraged to incorporate disruptive and emerging technologies. This may include innovative sensors, virtual or augmented reality, robotic contributions to post-storm coastal remediation, agent-based modeling of risk-induced emergent behaviors, and bio-inspired improvement of soil geotechnical characteristics.

Integration of lab and numerical experiments with test bed communities creates opportunities for transdisciplinary coproduction of knowledge by researchers (e.g., engineering, social sciences, physical sciences) and decision-makers, planners and residents.

In addition, the knowledge generated will expand current approaches to simulate storm impacts on communities to account for the combined effect of rainfall, groundwater flow, drawdown, wind and surge.

BROADER IMPACTS

Selection of demographically and socioeconomically diverse testbeds will include traditionally underrepresented communities in the hazard mitigation process, reduce social vulnerability, and promote community engagement in planning processes.

Incorporating local knowledge into projects at the proposal and development stage will lead to greater likelihood of successful technology transfer and policy implementation utilizing the campaign's research products.

Appendix A5: Comprehensive Numerical Simulation Platform for Hurricane and Tsunamis: From Source to Impact

RESEARCH CHALLENGE

This research campaign envisions a multi-year (5-10 years) research program consisting of multiple collaborative proposals that include the use of disruptive technologies.

It will lead to the development of a comprehensive numerical simulation platform for modeling hurricanes and tsunamis from source to impact on coastal communities. The numerical platform will be a multi-scale, multi-phase simulation that includes interaction with the natural environment, built environment, and population.

The comprehensive simulation platform will include the effects of wind, storm surge, surface waves, tsunami surge and bores, sediment transport, scour, and debris entrainment, damming, and impact.

Simulations will initiate either from the cyclone development or tsunami source and propagate at large-scale towards the coastline. Incrementally smaller scales will be employed to model the effects of near-shore bathymetric features, coastal topography and the built environment, which will be modeled in detail with appropriate fragility functions to simulate failure of weaker structures that contribute to entrained debris.

It will function either as a single mega-simulation tool including all components of the model, or as a suite of inter-operational simulation tools. Development and validation of the platform will be supported by laboratory experimentation, field reconnaissance observations and social science research.

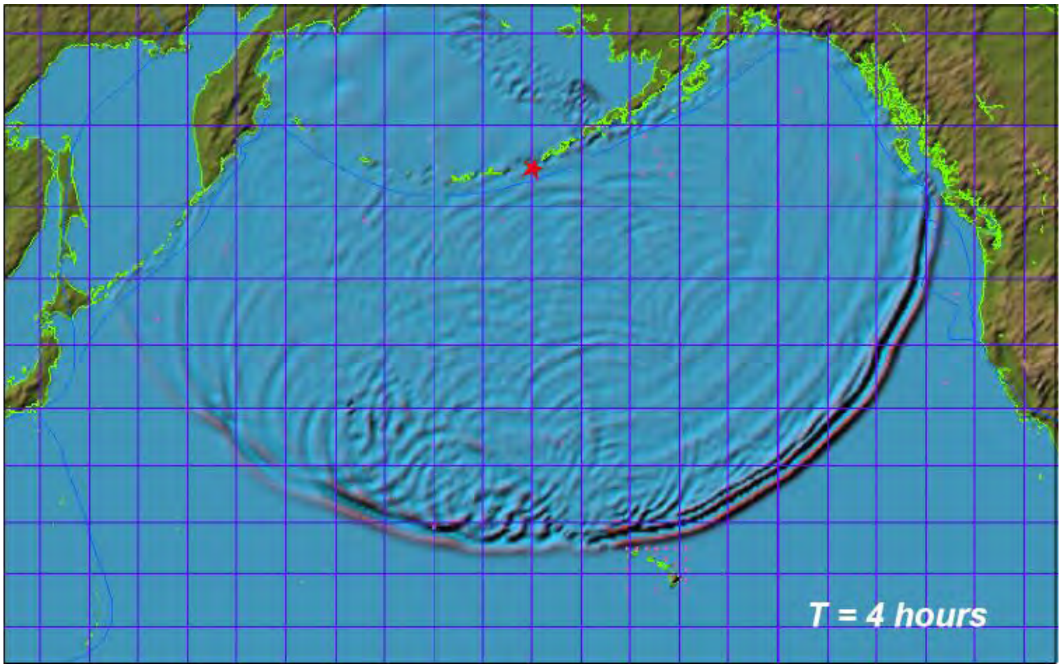
Simulation output will include time-histories of flow parameters at critical locations, hydrodynamic and debris impact loading on structures, sediment transport and scour, effectiveness of the community evacuation strategy, and casualty and loss estimation.

Once developed, the platform will be available for generating probabilistically based scenarios for non-emergency application to community planning, infrastructure design, loss estimation and impact modeling.

Machine learning will be used to develop predefined scenarios for evacuation support during future events using real-time input from the affected population and field sensors. The platform will be open source, portable and adaptive to future computational developments.

Population distribution and demographics will be included in an agent-based model to simulate evacuation of the affected population either to high ground or to vertical evacuation refuges.

A multi-disciplinary team including oceanographers, meteorologists, coastal, structural and geotechnical engineers, computer scientists, computational mechanics, social scientists, community representatives and policy makers, will develop the computational platform.



A simulated tsunami generated by a large subduction earthquake (Mw = 8.5) in Alaska-Aleutian Subduction Zone (Source: Pacific Marine Environmental Laboratory, NOAA).

INTELLECTUAL MERIT

Developing this multi-scale, multi-phase, multi-disciplinary, multi-hazard comprehensive computational platform will require development of advanced high-performance computational tools.

The platform will be validated using reconnaissance observations, casualty and loss estimates from past events. Innovative laboratory experiments will be performed in the NHERI tsunami wave basin (OSU) and wind facilities (UF and FIU) in collaboration with the Simulation Center, DesignSafe and Converge.

The experiments will utilize 3D printing to generate scale models of realistic natural and infrastructure components using materials with appropriate strength, stiffness and ductility. Test-bed communities with differing socio-economic, geo-political and population distributions will be modeled to verify the platform application to a wide range of realistic coastal communities.

BROADER IMPACTS

This campaign will provide a comprehensive simulation tool that will aid risk-informed decision making for coastal communities. The platform will enable evaluation of evacuation plans, community planning decisions, mitigation efforts, and associated benefit-cost analyses.

Implementation of this platform will lead to more resilient coastal communities with the associated reduction in casualties and financial consequences of future hurricanes and tsunamis.

Damage from earthquake and tsunami in Maule, Chile, 2010. The tsunami height was about 4-5 meters. (Photo: Walter D. Mooney, U.S. Geological Survey).

NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE

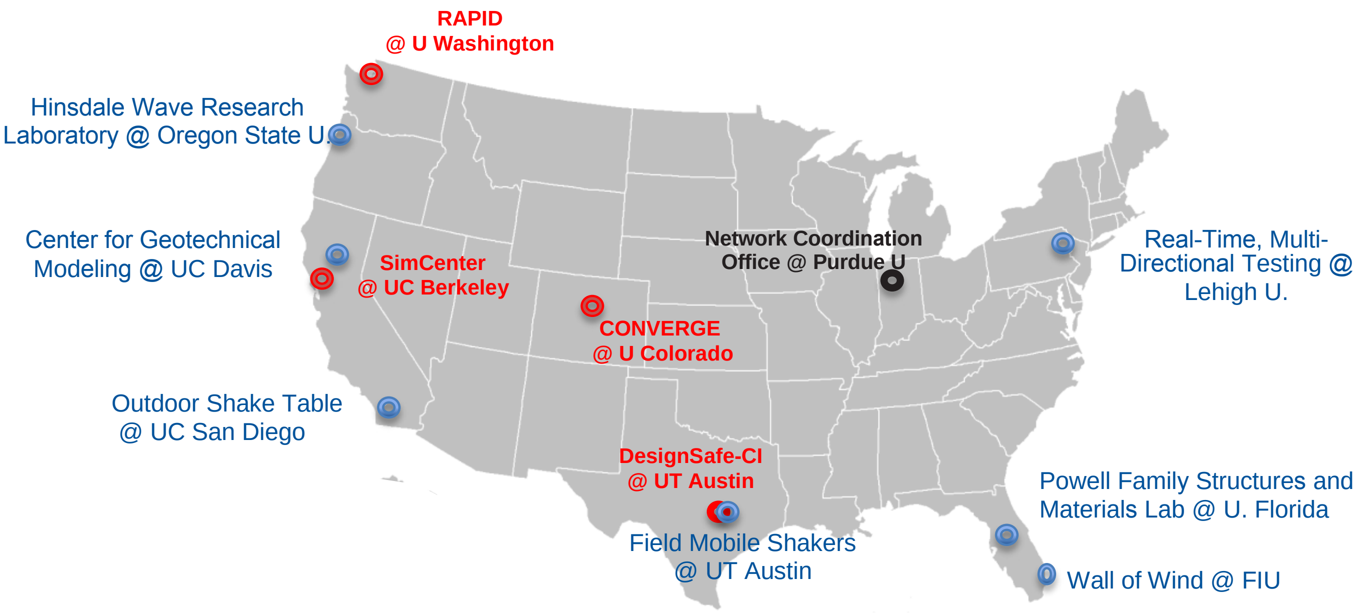
FIVE-YEAR SCIENCE PLAN

JANUARY 2020

APPENDIX B:

NHERI EXPERIMENTAL FACILITIES AND COMPONENTS

Appendix B: NHERI Experimental Facilities and Components



Appendix B1: Florida International University Wall of Wind

EXPERIMENTAL FACILITY OVERVIEW

The Wall of Wind (WOW) is a unique national, shared-use, multi-user, experimental infrastructure that enables frontier research and education to impart resiliency and sustainability of buildings and lifeline infrastructure, thus preventing wind hazards from becoming community disasters. The WOW is a large open-jet wind tunnel facility with distinct advantages over conventional wind tunnels, including:

- High-speed holistic testing at multiple scales in simulated hurricane wind speeds up to and including Category 5.
- Destructive tests to study progressive damage and failure modes of systems, sub-assemblies, and components to enhance their designs and improve performance.
- Wind-driven rain simulations to study water intrusion through building envelopes.
- Testing under extreme wind and rain environments to develop innovative mitigation strategies to attenuate wind damage and rain infiltration, and to validate efficacy and system-level integrity of mitigation devices and connections.
- Full- and large-scale aerodynamic and aeroelastic testing of large models in atmospheric boundary layer (ABL) flows at high Reynolds numbers to minimize scaling errors and better simulate the effects of finer geometrical details.
- Conventional boundary layer wind tunnel testing of small scale models in flows with various exposures and with full turbulence spectrum.

The 12-fan Wall of Wind at Florida International University will enable better engineering against tornadoes, hurricanes and other windstorms.

The WOW Experimental Facility Science Plan is aligned with the NHERI Vision as it includes:

- Predicting the lifecycle performance of civil infrastructure, from component to holistic system levels, under wind hazard events.
- Reducing the reliance on physical testing through providing data for validating advanced computational modeling and simulation capabilities.
- Building fundamental knowledge to evaluate wind effects and foster wind-hazard resilient and sustainable civil infrastructure and communities.
- Translating research into innovative mitigation strategies and technologies to reduce the impact of wind hazards.

The objective of the WOW Experimental Facility as part of the NHERI program is to enable an external, broadly inclusive user base to undertake fundamental research in various fields such as, among others, aerodynamics; fluid mechanics (supported by PIV measurements); synoptic and non-synoptic wind simulations; thermodynamic modeling; wind-induced vibrations; aeroelastic instabilities; stochastic processes and advanced statistical methods; structural reliability; fragility of building systems; rain infiltration mechanisms (e.g., direct rain admittance and surface runoff phenomena); wind simulation methodologies (physical simulation and validation of computational simulation), and non-linear structural behavior under wind loading.

Supporting Experimental Facility services include: Test specimen design, construction and instrumentation; test protocols and software implementation, operating the WOW; high definition video recording; data acquisition, archiving and curation of test-based data through NHERI DesignSafe; safety and user training; organize faculty engagement workshops and webinars; support users in NSF proposal development; and facilitate NSF projects.

Additional information regarding the facility and leadership group is available at the DesignSafe website: https://fiu.designsafe-ci.org.

RESEARCH OPPORTUNITIES

Fundamental Fluid Mechanics

A state-of-the-art Particle Image Velocimetry (PIV) system enables basic science research needed to reduce impacts of wind hazards on existing and new civil infrastructure and communities. The PIV helps to foster collaborative research that transcends traditional boundaries of wind and structural engineering and creates an additional niche in fundamental fluid mechanics research.

The PIV system with time-resolved and large field of view capabilities enables high-resolution measurements of unsteady flow characteristics and their effects on built and natural environments modeled at large physical length scales and near full-scale Reynolds number (Re). High spatio-temporal resolution of the PIV system enables simultaneous measurements of small-scale transient and turbulent, and large-scale mean velocity field characteristics.

This allows whole-flow-field measurements to study high Re fluid-structure interaction (FSI) directly applicable to several real-world problems. The capability supports ground-breaking cross-disciplinary research in, among others, building aerodynamics in high Re flows; active control to improve performance of rotor-based propulsion and energy systems; non-synoptic downburst flows and their effects; air pollutants dispersion in urban areas; wind-induced sediment erosion of coastal barriers; mechanics of loose-laid particle motions; renewable energy; natural ventilation; unmanned aerial vehicles aerodynamics, and civil infrastructure management under windstorms.

Validating Computational Fluid Dynamics and Other Numerical Simulation Methods

The WOW Experimental Facility helps to study the features of the flow-field, turbulence effects, and fluid-dynamic phenomena that lead to pressure patterns and responses.

The unique testbed, not currently existing at any other U.S. university at comparable scales, benefits researchers by providing data for validating Computational Fluid Dynamics (CFD) and other numerical simulation methods, and assessing and reducing uncertainties in numerical simulation results, thereby reducing reliance on physical testing.

Moreover, the WOW Experimental Facility has the ability to physically subject building components, holistic building systems, and scale models of such systems, to the impacts of hurricane force wind and rain. Detailed measurements of wind pressures, forces, wind-induced dynamic responses, and rain infiltration can be made under realistic hurricane conditions.

Thus the Experimental Facility has unique experimental resources and multi-scale testing capabilities that can be used for benchmark academic research on complicated wind-structure interaction problems to validate numerical modeling techniques.

Performance of Building Envelope

Research at the WOW Experimental Facility develops new insights into wind effects on building envelopes (including multi-layered cladding systems) and new designs to reduce wind loads and minimize rain infiltration.

The WOW Experimental Facility also enables researching the effect the effect of wind driven rain and the effects of rain, on air permeable building envelope systems which depend on pressure equalization. Performance of the existing building envelope components can be improved based on results from system-level experimentation. The Experimental Facility can also provide new knowledge on the strength, condition, remaining service life, and ability to resist penetration of wind-driven rain for cladding systems.

Effect of Shapes and Surroundings on Wind Loading

At the Experimental Facility, researchers can develop wind load time wind load time histories and coefficients for a wide range of different building shapes in various surroundings, accounting for interference and shielding effects. They can also conduct statistical studies of peak loads and variability introduced by non-uniform surrounding terrain, topography, and nearby buildings.

Tools are also needed to automate the process by taking advantage of widely available digital aerial photographic and elevation data. Moreover, machine learning techniques can be used to advance the research on wind loading on buildings and foster data-driven modeling. Overall, the results are intended to improve wind load provisions in codes and standards. The datasets will also be useful for designing buildings using Database Assisted Design methods.

Wind Effects on Small Structures

Traditional small-scale model wind tunnel testing to predict wind loads on large structures (e.g., tall buildings, long-span bridges) is well established. However, for small structures much larger model scales are needed to maintain modeling accuracy and minimize Reynolds number effects.

Rotating model for wind effects on small buildings (Photo: Arandam Chowdhury, FIU).

At these larger scale simulation of the low frequency end of the wind turbulence spectrum and of the turbulence integral scale is generally compromised by the test section size of the wind tunnel facility. However, the FIU team has recently developed a new Partial Turbulence Simulation (PTS) approach, verified by comparison with field data, which divides the turbulence spectrum into two distinct portions. This is a hybrid method combining experimental simulation of higher frequency turbulence with computer modeling of low frequency turbulence effects.

The method opens up whole new possibilities of obtaining more accurate wind load information on smaller structures by testing them at much larger scales than was previously possible (e.g. 1:10 rather than 1:100 for low-rise buildings, 1:3 rather than 1:30 for building appurtenances).

Applications have already been numerous: wind loads on solar panels; wind uplift on roof pavers; wind response of variable message signs, wind loads on low-rise structures, wind loads on canopies and sunrooms, etc.

The new PTS approach, and associated Experimental Facility software codes, will allow users to create new fundamental knowledge on bluff-body aerodynamics in high Re flows by minimizing errors due to scaling limitations.

Wind-Induced Vibrations

The ASCE 7 standard indicates that if a structure's natural frequency is above 1 Hz, it will not experience significant resonance effects. This provision was originally developed with buildings in mind. When applied to smaller structures and components, however, it can be very misleading. Examples are photovoltaic (PV) arrays, satellite dishes, shading devices, highway signage and signal systems, and architectural ornamentation (e.g., spires and trellises). Recent WOW testing indicated that wind-induced resonant vibrations may occur in PV systems with higher natural frequency (>10Hz). Similar behavior might be present on other building components and appurtenances.

Analytical modeling of resonant responses and combining with experimental data obtained from rigid models provides a methodology for assessing total wind-induced responses (background + resonant) of smaller structures, which can then be validated using system-level full scale tests.

The multi-scale modeling capabilities of WOW can help researchers in investigating wind-induced vibrations of not only small structures but also other structures including tall buildings, long span bridges, pedestrian bridges or special structures. Wind-induced motions affecting occupants can be studied and innovative methods of control can be developed. Overall, the WOW Experimental Facility can help users to study wind-induced vibrations and develop new designs or techniques to reduce vibrations to harmless levels and satisfy serviceability criteria.

Innovations in Mitigation Techniques

The WOW has proven to be an effective tool to test and validate wind mitigation devices, such as aerodynamic edge shapes to reduce roof suction, porous screens to mitigate wind load on rooftop units, and corner modifications to reduce wind drag on Variable Message Signs (VMS). These types of aerodynamic mitigation measures often require the large scale capabilities of the WOW to be properly validated. Other mitigation approaches such as damping to control wind induced vibrations can also be very effectively investigated in the WOW, including non-linear effects.

The WOW Experimental Facility provides system-level large scale testing capabilities to address these challenges and validate the effectiveness of retrofitting techniques and mitigation methods for reducing not only direct wind impacts and but also rain intrusion. System-level tests enable the structural integrity of the mitigation devices and their connections to be assessed under high winds. Such experimentation can inform risk modeling by comparing fragility curves for structures with and without mitigation. There are many fragility curves developed for seismic applications, but not so many for wind. For wind besides the fragility curves need to reflect vulnerability to water penetration as well as wind loading.

Engineered Building Systems and Automation in Construction

Considerable wind damage occurs due to the lack of construction quality control, particularly for the mass residential construction market. Houses are built using traditional methods by a multitude of contractors of varying levels of competence, experience, and workmanship. Maintaining quality while using numerous components and connections is a challenging task.

However, if a building can be assembled from a few large engineered components using well engineered connections, then quality control moves from the building site to the much more controlled conditions of the factory floor. Moreover, adaption under changing climate using construction automation has gained tremendous interest in the recent years. New research can transform knowledge in human-machine interaction and autonomous systems to minimize human errors, enhance safety, and increase efficiency and productivity, while achieving precision and economy in construction processes. Innovations in construction automation can be achieved using robotics, artificial intelligence (AI), and machine learning to enhance resilience and sustainability of the built environment and improve infrastructure performance under natural and human-induced stressors.

The Experimental Facility can help to test new types of hurricane-resilient engineered building assemblies and robotic construction practices that enhance community resilience. This also enables researchers to delve into minimal human intervention in construction processes to foster resilient communities, smart cities and networks.

Performance Based Wind Engineering

Current design procedures for resisting wind loads assume linear elastic material behavior. There is a lack of procedures for applying nonlinear analysis methods for wind loads. Such methods are needed to provide the ability to predict building performance to failure. Computational modeling of non-linear response of buildings and wood frame structures involves fundamental principles of non-linear deformations of members and connections.

The efficacy of such complex simulations can be validated using results from WOW Experimental Facility. This will facilitate the development of performance-based wind engineering. The topic of performance-based design in wind engineering is gaining significant attention in the wind engineering community. This can include not only tall buildings but also low- and mid-rise buildings, including cladding systems. The Experimental Facility can help explore application of PBD principles, involving experimentation on non-linear models to explore strength reserve, ductile behavior and plasticity, collapse mechanisms, and cladding performance under various levels of wind load.

Environmental Sustainability and Green Energy

The WOW Experimental Facility can help promote sustainable communities and engineered systems that support human well-being under a conducive environment.

1. The WOW can be used to model winds over complex local terrains using models constructed from Geographic Information System (GIS) data to maximize the efficiency of wind farms. This includes assessing the best sites, predicting the power that can be obtained and maximizing it through layout optimization and reducing wake effects. Dynamic turbine response to fluctuating wind loads can be studied using large-scale aeroelastic models, leading to substantially improved overall lifetime performance. Large-scale aerodynamic tests can help to better understand air flows near buildings to increase the use of small wind turbines on buildings as on-site renewable energy sources.

2. The WOW can be used to help improve Building Integrated Photovoltaic design by studying at full scale the effect of pressure equalization on wind uplift reduction. Experiments on passive aerodynamic cooling can help increase PV energy efficiency by reducing solar cell operating temperatures. The effect of turbulence on wind responses of PV racking systems can be studied.

3. Large-scale models can help study wind effects on natural ventilation in buildings with an aim to reducing non-renewable energy consumption for maintaining occupant comfort.

4. Smart cities can be designed through synergistic integration of critical infrastructures – such as sustainable buildings, smart transportation, communication systems, water networks, and power grids. Large-scale modeling can help investigate interdependencies and interactions of these systems under hazards.

5. The wind environment and microclimate around buildings including pedestrian safety and comfort can be studied.

6. Many high-and mid-rise buildings have issues with wind-induced noise generated by architectural façade elements. Multi-disciplinary research (including structural, architectural, mechanical, material science) can be conducted to understand and mitigate such effects.

Infrastructure Resiliency and Public Safety
Studying the aerodynamics and aeroelastic instabilities of various infrastructure systems (e.g., power delivery systems, communications towers, highway signs, intersection traffic signal systems, etc.) requires deep understanding of wind induced effects on these lifeline elements. Phenomena such as vortex shedding, galloping, and flutter need to be understood and designed for.

Computational modeling of these phenomena often needs very complex numerical simulations (such as aeroelastic analysis using moving grids). Such modeling techniques need to be calibrated and validated based on experimentation at 'holistic' system or subassembly levels (rather than at component levels)--a unique capability of the WOW Experimental Facility.

The Experimental Facility test-based full-scale dynamic and scale model aeroelastic data can inform and validate computational simulation of realistic fluid-structure interaction mechanisms for infrastructure safety research.

This can inform reliability-based risk modeling and make transformative improvements in understanding the wind dynamics of infrastructure assemblies and in developing high performance risk-consistent designs. Thus the WOW's multi-scale capability will help researchers to address growing concerns over infrastructure vulnerability.

Non-Synoptic Wind Effects
There is limited information about the loading effects on buildings from non-synoptic winds (e.g., as in tornado and downburst), and building occupants are in danger of death or injury from these types of events, in addition to significant property damage occurring annually.

The vertical velocity profile, wind speed time history, and turbulence fluctuations in non-synoptic winds are different from those in synoptic winds that are relatively well understood.

Thus, additional modeling or simulation of the wind effects from non-synoptic events needs to be conducted to account for the spatial and temporal localized nature of such winds.

An upgrade is ongoing at the WOW Experimental Facility to introduce a new downburst simulator that can be used to study non-synoptic wind effects and structure's response at large scales. The spatial localization of downburst can lead to non-uniform and non-symmetric loading on long span or tall structures, while the temporal localization of the event causes a sudden peak of the mean wind speed over a very short duration.

The dynamic responses of different structural components subjected to the downburst's varying-mean and fluctuating components are expected to vary from those resulting from synoptic wind excitation. Research can be performed to gain fundamental understating of how the aerodynamic loading on and dynamic responses of structures are different from those in straight-line winds.

Appendix B2: Lehigh University
Large-Scale Multi-Directional Hybrid Simulation Testing

EXPERIMENTAL FACILITY OVERVIEW

The Lehigh NHERI Experimental Facility, known as the Multi-Directional Real-Time (RTMD) Hybrid Simulation Facility, operates in the Multi-Directional Testing Laboratory at the Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center at Lehigh University.

Large-scale hybrid simulation of a self-centering steel moment resisting frame building under simulated earthquake loading.(Photo: Jim Ricles, Large-Scale Multi-Directional Hybrid Simulation Testing, Lehigh University).

Over 25 years of ATLSS Center operations, including 12 years as a NEES@Lehigh equipment site and the past three years as a NHERI Experimental Facility, the Lehigh NHERI Experimental Facility has acquired a unique portfolio of equipment and instrumentation, has assembled a well-trained and skilled staff, and developed state-of-the-art algorithms, software, and tools for real-time integrated simulation control to enable large-scale real-time hybrid simulations to be performed on a routine basis.

The strength of the Lehigh NHERI Experimental Facility is accurate large-scale simulations of the effects of natural hazard events on civil infrastructure.

The unique equipment portfolio (capabilities existing only at Lehigh) includes:

- Three 1700 kN and two 2300 kN servohydraulic actuators with 1000 mm stroke and maximum velocities of up to 1140 mm/sec.
- An hydraulic power supply system consisting of 5-454 lpm pumps and a 3030 liter accumulation system enables earthquake effects on structures to be sustained for more than 30 seconds during a large-scale real-time hybrid simulation.
- A real-time integrated IT control system, which integrates laboratory data acquisition, computational simulation, and servo-hydraulic actuator control in a single IT system.
- The ATLSS Center with its 3-D reaction wall-strong floor laboratory, skilled laboratory staff (instrumentation, construction, hydraulics, and control) and additional resources.

Other ATLSS resources include additional servo-controlled actuators, instrumentation, digital image correlation system, mechanical testing laboratory, metallography and microscopy laboratory, non-destructive evaluation laboratory, machine shop, offices for visiting researchers.

Additional information regarding the facility and leadership group is available at the DesignSafe website https://lehigh.designsafe-ci.org/facility/overview/

RESEARCH OPPORTUNITIES

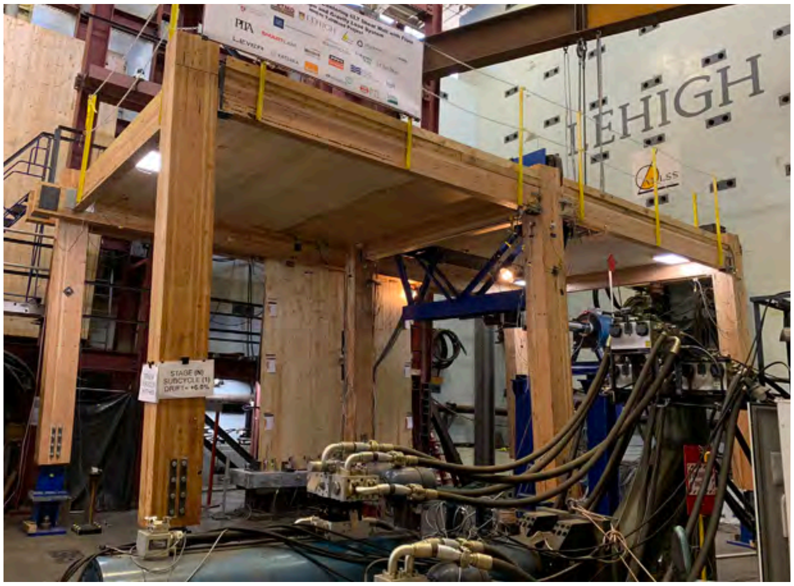
Characterization of Large-Scale Response-Modification Devices

Stakeholders are interested in promoting resiliency of their structures to the effects of natural hazards. Consequently, there has been an interest in developing new and innovative response-modification devices and structural systems that reduce damage and downtime of a building following an extreme natural hazard, such as wind or an earthquake event.

The equipment at the NHERI Lehigh Experimental Facility can be used to characterize large-scale devices that are placed in structural systems for the purpose of modifying the building response in order that the system become more resilient to these events.

Examples of these devices include passive controlled dampers (e.g., nonlinear viscous dampers, elastomeric dampers, negative stiffness dampers), semi-active controlled dampers (e.g., magnetorheological dampers), and yielding devices (e.g., buckling restrained braces).

Several testbeds and an environmental chamber exist at the Lehigh Experimental Facility that can be used to perform the characterization tests on response-modification devices considering as parameters: displacement amplitude, frequency of loading, and ambient temperature. Such data is useful to develop and calibrate computational models for the purpose of performing numerical simulations to investigate the effectiveness of these devices in improving the resiliency of the building.



Large-scale multi-directional testing of a cross-laminated self-centering shear wall-floor diaphragm system under simulated earthquake loading. (Photo: Jim Ricles, Large-Scale Multi-Directional Hybrid Simulation Testing, Lehigh University).

Use of Supplemental Damping Systems in Mitigating the Effects of Natural Hazards

A number of building codes have published criteria for using supplemental damping systems to mitigate the effects of earthquake and wind. However, experimental validation of the criteria is lacking, enabling improved design criteria and efficiency to be developed and utilized by the profession.

An example is the allowable reduction of the design base shear to 75% of the code seismic design base shear. Is this an acceptable value that results in an adequate margin against collapse under extreme earthquake or wind loading? A testbed exists at the NHERI Lehigh Experimental Facility that will enable real-time hybrid simulations to be performed on lateral load resisting systems outfitted with dampers, or other types of response modification devices.

The large-scale dynamic actuators in combination with the multi-directional reaction wall enables large-scale specimens to be tested. Through real-time hybrid simulation, the interaction of the lateral load resisting system, the supplemental damper system, the gravity load system, and soil and foundation system can be investigated.

Real-time Hybrid Simulation of Semi-active Controlled Base Isolation Systems

Base isolation has become a popular technique to mitigate the effects of strong ground motions caused by earthquake that lead to damage and downtime. However, there are still a number of research questions that need to be addressed, particularly the effects of near-fault earthquake ground motions on base-isolated structures.

It has been shown analytically that conventional base-isolated systems do not perform as well under these type of ground motions compared to far-field ground motions. A possible solution is to incorporate semi-active devices to create a semi-active controlled base isolation system. Real-time hybrid simulations can be performed at the NHERI Lehigh Experimental Facility, where the isolation system is located in the laboratory (i.e., is the experimental substructure) and kinematically linked to the superstructure through their common degrees of freedom.

The superstructure is modeled numerically through the analytical substructure. This is an economical approach to test the complete system, since only the isolators need to be physically constructed, enabling many tests to be performed using the same testbed and isolators.

The NHERI Lehigh Experimental Facility has hardware in its real-time integrated control system that enables researchers to implement and study different semi-active control laws for the isolation system.

Geographically Distributed Hybrid Simulation
Often the size of the test specimen exceeds the capabilities of the experimental testing facility (e.g., number of testbeds, actuators, laboratory-testing space).

The NHERI Lehigh Experimental Facility has capabilities to team up with other testing laboratories to perform geographically distributed hybrid simulation of structural systems. An example of a geographically distributed hybrid simulation is where several experimental substructures are located at Lehigh and at the collaborator's laboratory.

A conductor, using the Internet with communication protocols to issue command displacements and obtain feedback forces, directs the simulation. This method can be used to investigate the response of a structure to wind or earthquake hazards with large response modification devices. Testbeds for the devices are located amongst the laboratories. The devices are linked to the remaining part of the structure that is modeled numerically (e.g., analytical substructure) for the hybrid simulation.

Large-scale damper testbeds for characterization and real-time hybrid simulation of structural systems subjected to wind or earthquake loading (Photo: Jim Ricles, Large-Scale Multi-Directional Hybrid Simulation Testing, Lehigh University).

The effects of soil-structure interaction on the response of a structural system to wind or earthquake hazards can also be investigated using this simulation approach.
Components of the foundation can be located in a soil box either at Lehigh or remotely at another laboratory, where this experimental substructure is linked to other experimental substructures of components of the superstructure located at Lehigh.

Lehigh NHERI RTMD Large-scale Hybrid Simulation Facility: Enhancing the Resiliency of the Built Environment

The Real-Time Multi-Directional (RTMD) Large Scale Hybrid Simulation NHERI Facility at Lehigh University provides researchers access to unique equipment and simulation tools. Keri Ryan, associate professor of civil and environmental engineering at the University of Nevada, Reno used the facility to investigate the performance of non-structural components in buildings subject to multi-directional earthquake ground motions. This study would not have been possible at her home institution.

With the NHERI Lehigh facility, however, Professor Ryan was able to develop innovative non-structural component details that remain damage-free under strong earthquake ground motions and advance community resilience.

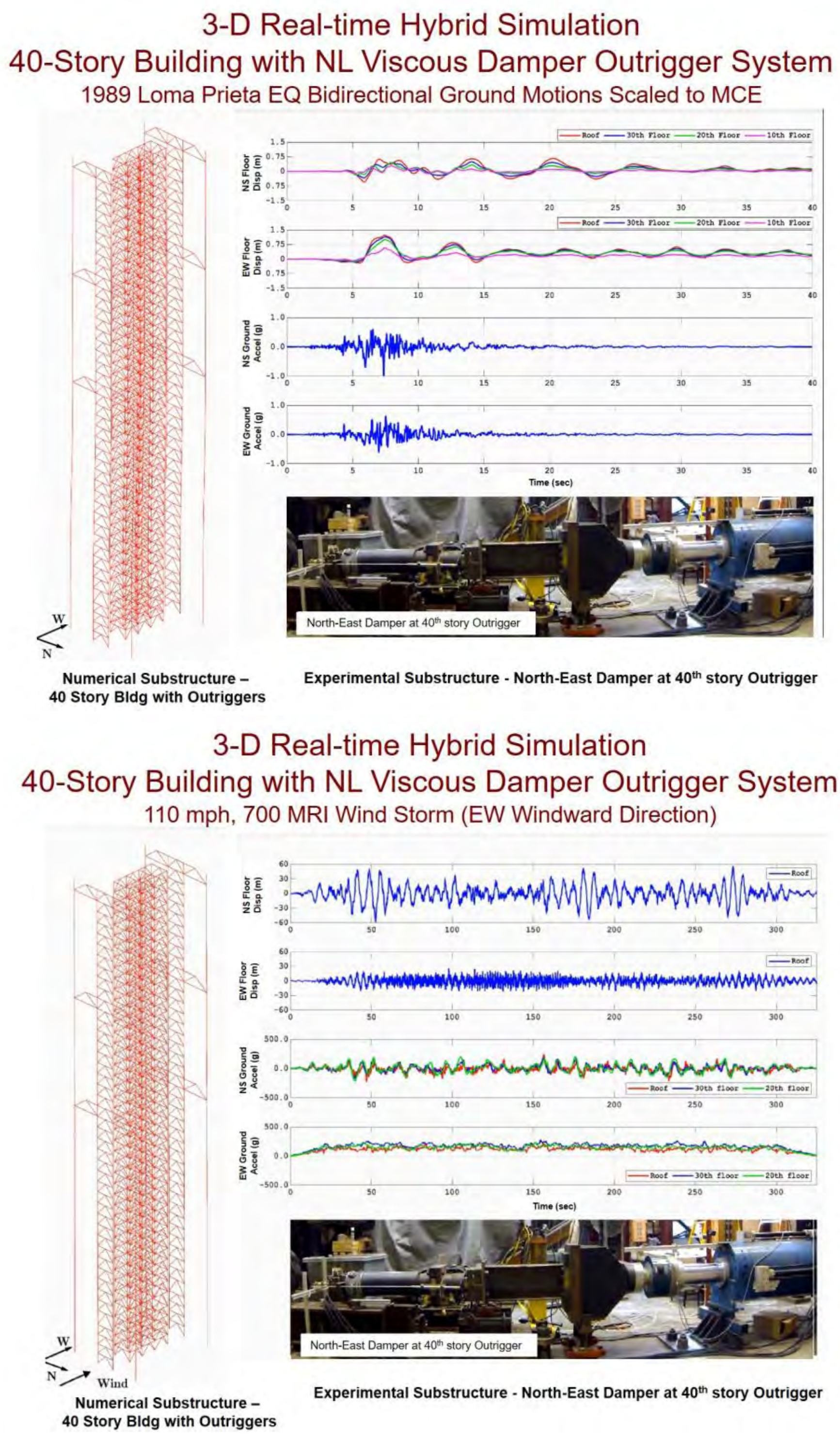
Building Community Resilience to Natural Hazards Using Large-scale Hybrid Simulation

The Lehigh University Real-Time Multi-Directional (RTMD) Large Scale Hybrid Simulation NHERI Facility is the largest facility of its kind in the nation.

This unique, shared-use facility is dedicated to enabling transformative research that reduces the impact of natural hazards and advances the resiliency of the nation's civil infrastructure.

Researchers have access to state-of-the-art equipment and simulation tools to study the response of civil infrastructure to 3D wind or earthquake loading, where the complete structural and foundation systems are included in the investigation.

This is accomplished through real-time hybrid simulations that combine physical experiments with state-of-the-art computer-based simulations for evaluating the performance of large-scale components and systems.



3-D large-scale real-time hybrid simulations of structural systems subjected to wind and earthquake loading (Image: Jim Ricles, Large-Scale Multi-Directional Hybrid Simulation Testing, Lehigh University).

Appendix B3: Oregon State University
O.H. Hinsdale Wave Research Laboratory Experimental Facility

EXPERIMENTAL FACILITY OVERVIEW

The Experimental Facility for coastal surge, wave and tsunamis is located inside the O.H. Hinsdale Wave Research Laboratory (HWRL) at Oregon State University.

It is the largest coastal engineering laboratory at any U.S. academic institution. The Experimental Facility consists of a three-dimensional Directional Wave Basin (DWB) and a two-dimensional Large Wave Flume (LWF). The DWB measures 48.8 m (160 ft) long by 2.1 m (7 ft) deep by 26.5 m (87 ft) wide, and has a maximum water depth of 1.37 m (4.5 ft).

The DWB is equipped with 29-segmented piston-type waveboards. It is capable of generating long-stroke solitary waves to simulate tsunamis as well as either periodic or random waves to simulate the wave spectra associated with wind storms. It can generate waves at mean angles to the wavemaker or at multiple angles to simulate a directionally spread (short-crested) sea state.

The LWF measures 104 m (342 ft) long by 4.6 m (15 ft) deep by 3.6 m (12 ft) wide and has a maximum still water depth of 2.7 m (9 ft). The LWF wavemaker is a large- stroke, piston-type wavemaker capable of generating unidirectional waves, consisting of long-stroke solitary waves to simulate tsunamis or periodic or random waves to simulate the wave spectra associated with wind storms.

The facility is equipped with a suite of in-situ instrumentation. The free surface is observed with surface-piercing wire wave gages and ultrasonic range finders. Water particle velocities are observed with up to 16 acoustic Doppler velocimeters. Fluid pressures are observed with strain-gage-based pressure sensors, and total loads on structures are observed with load cells at capacities up to 50 kip.

The facility is capable of deploying these sensors in fixed locations or from movable instrument platforms that span either the LWF or the DWB. It is equipped with survey and bathymetric profiling instrumentation for locating sensors in the tanks or for observing erosion or deposition of the bed.

Two-dimensional wave tank with 104m length, 4.6m deep and 2.7m width with wave generation at top of photo (Photo: Dan Cox, Hinsdale Wave Research Laboratory, Oregon State University).

Observations are made using a data acquisition system (DAQ) that is synchronized with CUT (Coordinated Universal Time) and across multiple runs of the same wave conditions to provide synoptic data sets. The DAQ is operated on a university-wide site license of National Instruments LabVIEW and updated and tested annually.

The facility also operates remote-sensing instrumentation including stereo (3D) PIV and surface tracking, six DOF motion capture, and HD video cameras for tracking wave runup or large-scale hydrodynamic features. Where applicable, all instrumentation is regularly and traceably calibrated.

The overall vision for the facility is to support the broader vision of NHERI to increase the resilience of civil infrastructure and communities to coastal storms and tsunamis. In this context, resilience is the ability of a system to absorb and recover from a sudden disturbance (e.g., NRC 2012).

Earthquakes and windstorms represent multi-hazards, and this facility will contribute to the broader societal goals of reducing the loss of life and human suffering, decreasing direct economic damages, and increasing the rate at which socio-economic recovery can occur for coastal hazards.

Additional information regarding the facility and leadership group is available at the DesignSafe website: https://oregonstate.designsafe-ci.org/

RESEARCH OPPORTUNITIES

This Experimental Facility is available for the following key NHERI five-year research topics:

Surge/Wave and Tsunami Inundation Hazards

A grand challenge for overland flow is to model the hazard intensity over scales ranging from entire regions (several hundred kilometers) to subassemblies of structures (several meters). Current state of the practice assumes 'bare earth' models, meaning that the effect of the built environment is not modeled in detail, although it is known that the built environment has significant influence on the local flow field.

Other key research questions include how to account for the time-varying conditions—for example the changing bathymetry and topography due to coastal erosion and roughness due to damage/failure of buildings and other infrastructure.

NHERI Hinsdale Wave Research Laboratory: Resilience of coastal communities to storm waves and tsunami hazards

The Hinsdale Wave Research Laboratory serves as a state-of-the-art engineering research, education, and outreach center related to tsunamis caused by earthquakes and coastal waves and surge caused by windstorms. Through NHERI, the Large Wave Flume and the Directional Wave Basin have been made available to the research community to advance the resilience of civil infrastructure and communities to coastal storm and tsunami hazards.

Under NHERI, the HWRL has conducted experiments on the interaction of waves and coastal structures, surf-zone dynamics, submarine tectonics, tsunami sheltering by offshore islands, macro-roughness, waterborne debris and overland flow, among other studies to increase the resilience of coastal communities.

(Photo: Dan Cox, Hinsdale Wave Research Laboratory, Oregon State University).

Hinsdale Laboratory three-dimensional wave basin (Photo: Dan Cox, Hinsdale Wave Research Laboratory, Oregon State University).

Additional challenges related to overland hazard include the quantification of flood-borne debris hazards that are related to debris impact, debris damming, and debris removal challenges.

The inundation and subsequent return flow also generate significant currents and other navigational hazards. It is generally accepted that velocity is more difficult to quantify compared to the water level, so the generation of current hazards remains an open area of research. The generation of tsunamis from landslides remains an open area of research. Although it is difficult to model climate change effects over the long term, anticipated changes to sea level rise can be modeled through static changes to water level in the flume and basin.

Surge, Wave and Tsunami Loads

Estimating surge/wave and tsunami loads on coastal infrastructure, including building, transportation, water, power, and communication lifelines, remains an engineering grand challenge.

Although significant progress has been made for offshore and coastal structures which regularly experience extreme wave loads, similar progress has not been made for near-coast structures for which these conditions are rare. Our ability to accurately predict the pressure distributions for both horizontal and uplift loads remains a challenge. Moreover, because the wave climate is random in nature, the wave loading will follow some distribution. The probabilistic nature of extreme wave loads for a given sea state remains an open research question.

The effects of cyclic loading from long-duration storms, multiple storms, and/or multiple tsunami waves, particularly cyclic loading from conditions less than the design conditions and its impacts on coastal infrastructure, is an important research area and within the capabilities of the Experimental Facility.

Related to the issue of wave loads, additional challenges include wave/surge and tsunami damage functions. Some progress has been made since the 2004 Indian Ocean tsunami and the 2011 Japan tsunami to develop empirical fragility curves for buildings and bridges. Additional work has been done to develop flood damage functions that may be suitable for coastal environments.

However, the development of probabilistic approaches for community scale risk assessment remains a grand challenge. Load combinations for simultaneous flood hazards such as the static buoyancy due to flooding, the hydrodynamic drag due to currents, and the impulsive forces due to waves remains a research question. Performance-based design for coastal structures also remains a research question.

Building performance over the lifecycle of the building/infrastructure accounting for conditions specific to the coastal environment like corrosion and their impact on design performance are important research questions. Corrosion can be studied through proper aging of the material specimens prior to testing at the Experimental Facility. The Experimental Facility can also be used to evaluate the effectiveness of various flood proofing techniques and other methods to mitigate the direct damage of coastal hazards.

Coastal Erosion and Scour

Our nation relies on coastal beaches and dunes to mitigate the effects of extreme storm surges. A grand challenge is to account for coastal erosion during extreme events to quantify overtopping of dunes, revetments, seawalls and other measures to mitigate storm surge. Moreover, coastal infrastructure including pile foundations, slab on grade construction, seawalls, surface transportation, and buried pipelines depend on an understanding of the local scour to design resilient infrastructure.

Natural and Nature-Based Features for Coastal Hazard Mitigation

Similar to our reliance on beach nourishment and dune construction, the U.S. is relying increasingly on natural and nature-based features (NNBF) including coastal reefs and wetland features for coastal hazard mitigation because NNBF provides a wide range of benefits including economic and ecological functions.

Although the ecological good and services are reasonably well known, the capacity of such systems to provide adequate protection is still an open research question. These systems are also expected to change over seasonal and decadal time scales, further complicating our understanding of the performance of these systems. The integration of such systems into multiple lines of defense also remains on open research question. The Experimental Facility is suitable for modeling beach/dune systems for coastal defense as well as different dune construction techniques and the hybrid construction of dunes. The use of artificial and live vegetation is also possible at the Experimental Facility.

Numerical Model Development and Benchmarking

Significant progress has been made on numerical modeling of hydraulic flows at a range of scales. Direct Numerical Simulation (DNS) is only feasible at scales much smaller than what is necessary for coastal hazards engineering, therefore suitable methods for turbulence closure remain a challenge. Additional challenges include multi-phase flow, including air-water-sediment.

For example, accounting for air entrainment is necessary to capture impulsive breaking waves and the uplift for complex shapes which frequently trap air. The coupling of fluid structure models is also a research question. Local wave impact and structural component elasticity occur at a significantly smaller time scale (micro- to milli-seconds) than the surge, wave and tsunami load durations (seconds to kilo-seconds), necessitating multi-physics models and multi-time scale computation. Enforcing interface compatibility and matching time step are paramount for accurate long-term response prediction. Additional topics for numerical modeling and benchmarking include wave and tsunami runup, wave breaking and bottom boundary layer turbulence, sediment suspension and transport, and multi- phase (air-water-sediment) dynamics.

Appendix B4: Purdue University

FACILITY OVERVIEW

The Purdue-led Network Coordination Office (NCO) center (a) serves as a focal point and leader of a multi-hazards research community focused on mitigating the impact of future earthquakes and windstorms, and related hazards such as tsunamis and storm surge on our nation's physical civil infrastructure; (b) leads education and outreach activities; (c) works with our partner NHERI Experimental Facilities to ensure the efficient testing and user support within a safe environment; (d) centrally coordinates the facilities' schedules, and facilitates shared technical knowledge and best practices among the NHERI Experimental Facilities; and (e) develops strategic national and international partnerships.

The objective of the NCO is to coordinate NHERI activities with the other awardee components and thus to form a cohesive and fully integrated global natural hazards engineering research infrastructure that fosters collaboration in new ways.

The mission of NHERI is to provide the earthquake, wind, coastal engineering, and social sciences communities with access to research infrastructure and education and community outreach activities focused on improving the resilience and sustainability of the civil infrastructure against earthquakes, windstorms, and associated natural events such as tsunami and storm surge in coastal areas.

The NCO team is a multi-disciplinary, multi-institution, and diverse group of leaders. It combines expertise in civil, earthquake, structural, coastal, wind, geotechnical, and industrial engineering, as well as political and social science.

Additional key senior personnel bring to the team experience in practice and development of codes and guidelines; and the application of numerical models based on unstructured grids to coastal dynamics, with notable expertise in tide and storm simulations.

Natural Hazards Engineering Research Infrastructure (NHERI)

COLLABORATION OPPORTUNITIES

5-Year NHERI Science Plan

The NCO has been charged with leading the nation's multi-hazards community in the development of the five-year research agenda that will elucidate grand challenges, key questions, and research objectives for the engineering and social science communities studying earthquake, wind, and coastal hazards.

The five-year NHERI Science Plan was developed in two steps. As soon as all NHERI components were awarded, the NCO collected all awardee Science Plan components and established a task group to develop the first draft in the first three months of the award, starting July 1, 2016. The community-driven process included collecting broad input and ideas from a number of stakeholders as well as engaging leaders in the earthquake, wind, coastal engineering, and social science fields in the task group to synthesize input into a comprehensive plan.

The first edition of the NHERI Science Plan was published on the NHERI website (designsafe-ci.org) in July of 2017, after reviews by the Network Independent Advisory Committee (NIAC), the User Forum, NHERI Council, and NSF. Then the Science Plan was issued for a four-week public review process. For final publication the task group reviewed all comments and responded accordingly.

Governance - User Forum (UF) and Network Independent Advisory Committee (NIAC)

The UF and NIAC are NHERI's governance committees. The Council of awardees nominates individuals for invitation to join the NIAC, while the UF members are nominated and elected by NHERI users. The role of NIAC is to provide independent guidance and advice to the NHERI Council.

The NIAC's distinguished membership encompasses the areas of activity of NHERI so that the community is properly represented in this important governance committee. The NIAC works independently to assess NHERI's continuing value added and the impact of NHERI on research activities and educational advancements. It also reviews progress, plans and performance of NHERI Awardees (Experimental Facilities) and produces an annual report. The annual report is available on the DesignSafe-ci.org website. It is also tasked with providing an assessment of the transparency and efficiency of the NCO's facility scheduling protocols.

Development of the 2020 edition of the Science Plan relied on additional input from the community through: (i) reviews conducted during the NHERI Summer Institutes in 2017, 2018, and 2019; (ii) public comments received during the first three years of NHERI operations and responses from the authors of this version; and (iii) input received from the participants during the Science Plan Workshop held in Alexandria, VA on March 18-19, 2019 (summarized in the workshop final report).

Continued input from the community is welcomed via DesignSafe-CI, and at occasional workshops, to improve the plan to serve as a resource for the community developing research and education proposals for submission to NSF funding opportunities.

Tornado damage at a high school, Greensburg, KS, 2007 (Photo: FEMA).

The User Forum (UF) committee is a NHERI-wide group focused on providing the NHERI Council with independent advice on community user satisfaction, priorities, and needs relating to the use and capabilities of NHERI. The elected volunteers of the UF bring input from the community into NHERI operations, assess the effectiveness of the support to NHERI users, and contribute to the Network Coordination Office (NCO) and NHERI-wide efforts to build a community of satisfied users.

NHERI REU 2019 participants touring the DesignSafe cyber infrastructure super computers (Photo: Julio Ramirez).

The UF committee is engaged in the development and continuous update of the NHERI-wide Science Plan. The User Forum is engaged in technology transfer, dissemination of impact, and sharing lessons learned and experiences of the various hazard communities. The UF functions as an additional voice of the community within the governance of NHERI. For more information on these groups visit: https://www.designsafe-ci.org/facilities/nco/governance/

Education and Outreach Activities
Multiple avenues for community participation are available through the various NHERI-wide education and community outreach activities led by the NCO. The NHERI Education and Community Outreach (ECO) Committee, comprised of representatives from each of the NHERI sites, serves as the strategic leadership developing educational programs for the network.

Two flagship events include the NHERI REU program and the NHERI Summer Institute, which engage undergraduates, graduate students, and early career faculty in natural hazards engineering research. These events focus on inspiring and generating the next generation of engineers engaged in natural hazards research and practice.

The NHERI Research Experience for Undergraduates (REU) summer program provides faculty-mentored research experiences for undergraduate students across 10 NHERI experimental, reconnaissance, simulation, and cyberinfrastructure sites. REU students attend online research meetings and career workshops. They present their research and research posters as well as tour NHERI sites during the NHERI REU Research Symposium. In three years, a total of 77 undergraduates from the across the U.S., including Hawaii and Alaska as well as Guam and Puerto Rico, participated in the NHERI REU program: 31% first-generation college students, 56% female, and 42% underrepresented minority.

The Summer Institute for early career faculty, practicing engineers and architects, and senior-level graduate students, is another key activity for the NHERI community. Each year, NHERI awards approximately 20 travel grants for early career faculty and senior-level graduate students to attend the Summer Institute. The 3-day workshop presents NHERI resources, National Science Foundation (NSF) grant writing tips, and a CAREER workshop and panel, along with many networking opportunities. As of August 2019, 23% of NHERI Summer Institute alumni successfully secured grant funding for their research.

Engagement with Community
NCO committees such as the Scheduling Committee, Education and Community Outreach Committee and others provide additional avenues for the community to participate in the NHERI network.

Summer Institute team preparing a mock proposal (Photo: Karina Vielma-Cumpian, UTSA, NCO).

There are many other opportunities to engage the community. The NCO will be working with the users and the broader NHERI network to achieve the NHERI vision of global research infrastructure where users are empowered to achieve enhanced national resilience and sustainability of civil infrastructure with fewer fatalities, less interruption to societal functions, and reduced economic loss by reducing the impact of earthquakes, windstorms and associated natural hazards such as tsunami and storm surge.

NHERI Technology Transfer Committee
The Technology Transfer Committee is made up of 18 volunteer individuals knowledgeable in development of codes, standards, and other means of implementing research associated with mitigation of hazards from earthquakes, wind storms, and flooding from tsunami and storm surge.

The committee regularly reviews NHERI research projects for results than can be implemented in the near-term. If potential implementers do not know such results, the committee will facilitate transfer of the findings.

The committee has also developed a paper describing typical implementation paths of natural hazard research results. The paper is particularly targeted to early-career researchers, but it stands as a resource for all NHERI researchers to facilitate implementation.

Appendix B5: University of California Berkeley SimCenter

FACILITY OVERVIEW

The SimCenter Experimental Facility is developing technologies to provide access to computational modeling and simulation software tools, user support, and educational materials needed to advance the capability to simulate the impact of natural hazards on civil infrastructure.

The SimCenter's approach is to create software technologies that can seamlessly integrate a broad array of simulation software with high-performance computing platforms and data repositories. In addition to assembling tools to streamline computational workflows, the SimCenter offers training to educate and empower the next generation of researchers to use these tools.

The SimCenter provides an open-source framework to integrate modeling and simulation tools to:

- Address earthquakes, windstorms, and related natural hazards of tsunami and storm surge.
- Tackle complex, scientific questions of concern to disciplines involved in natural hazards research, including earth sciences, geotechnical and structural engineering, computer sciences, architecture, urban planning, disaster and risk management, decision science, public policy, and finance.
- Utilize machine learning to facilitate and improve modeling and simulation using data obtained from experimental tests, field investigations, and previous simulations.
- Integrate uncertainty propagation and quantification at all levels of the software suites through traditional and state-of-the-art schemes.
- Utilize high-performance parallel computing, data assimilation, and related capabilities to smoothly combine software applications into advanced workflows with embedded complexity.
- Extend and refine software tools for carrying out performance-based engineering evaluations and supporting decisions that enhance the resilience of communities susceptible to multiple natural hazards.
- Utilize existing applications that already provide many of the components required for the complex computational workflows.

The SimCenter will:

- Develop a computational framework to support decision-making to enhance community resilience to natural hazards in the face of uncertainty.
- Seed the framework with enough data and connectivity to existing simulation tools that it can be employed in the near-term and thus improve as users identify weakness and new needs.
- Create a framework that is sufficiently flexible, extensible, and scalable so that any of its components can be enhanced to improve the analysis and thereby better meet the needs of a user group.
- Provide an ecosystem that fosters collaboration between scientists, engineers, architects, urban planners, decision-makers, and others who seek to improve community resilience to natural hazards.

The SimCenter is working closely with the DesignSafe team to make computational tools for NHERI research and education through the DesignSafe Research Workbench. As the SimCenter develops these tools, the SimCenter invites NSF researchers to participate in the development, trial studies, and evaluation of the software by incorporating simulation-related research activities into their research plans. Because the computational workflows will be run through DesignSafe, the studies are limited to simulation software and datasets accessible through DesignSafe.

Examples of computational simulation tools either currently available or expected to be available in the coming year include:

- Finite Element Modeling: OpenSees, LS-DYNA*, ABAQUS*, ANSYS*
- Computational Fluid Dynamics: OpenFOAM, ADCIRC
- Statistics, Uncertainty Propagation, Optimization: DAKOTA, R, MATLAB*

*Note – requires users' license to access on DesignSafe

In future years, simulation tools will be addressing regional modeling, including UrbanSim and other software to analyze distributed infrastructure systems.

Additional information regarding the SimCenter, tool development and supported software is available at the DesignSafe website: https://www.designsafe-ci.org/facilities/simcenter/.

RESEARCH OPPORTUNITIES

Included below are examples of topics that researchers are encouraged to consider in research proposals where collaboration and utilization of SimCenter technologies can be applied to address NHERI research challenges.

Validating Computational Simulations and Estimating Model Parameters using Experimental Data

Computational workflow tools will facilitate the integration of advanced computational modeling software with statistical and optimization tools to calibrate and validate computational simulations with data from tests conducted at the NHERI and other state-of-the art experimental facilities as well as post-disaster observations collected through the NHERI Rapid Center.

For example, the workflows can automate the calibration of model parameters in simulation software for solid and fluid mechanics, such as OpenSees, OpenFoam, LS-Dyna, and others to experimental test data, through statistical optimization algorithms in Dakota (https://dakota.sandia.gov/). Seamless integration of the simulation tools on high-performance computers will facilitate parameter estimation across multiple test series to provide robust estimates of central values (medians or means) and the associated dispersion.

Applications can involve experiments conducted at any of the NHERI experimental facilities, including structural labs, wind facilities, geotechnical facilities, and tsunami basins, or data collected from past earthquakes from instrumented structures and lifeline facilities.

Observations from such calibration studies and parameter estimation can be harnessed through knowledge-based tools which will leverage the learning from such studies to improve modelling technologies.

Developing Damage and Loss Functions for Building and Infrastructure Components and Systems

Fragility functions for relating loading demand parameters to damage and loss are essential for performance-based methods to assess the performance of buildings and resilience of communities.

Uncertainty quantification tools coupled with computational simulation models, laboratory test data, and high performance computing provide unprecedented capabilities for extrapolating experimental studies of component damage fragilities to address a wider range of conditions and to extend from component-level damage to system-level damage. Coupling of computational damage simulation data with post-disaster loss data (e.g., repair costs and downtime) can enable further development and calibration of loss functions.

Performance-Based Engineering for Natural Hazard Risk Mitigation

Performance-based engineering and design require integration of models and data to characterize natural hazards and propagate their damaging effects on buildings and civil infrastructure, including the impact of the damage on socio-economic factors. In concept, the performance-based framework is straightforward; however, the required integration of simulation models, data, and uncertainty propagation creates many challenges.

The SimCenter is developing data and meta-data models for performance-based engineering applications necessary to link data sets and simulation tools to go from hazard characterization to physical response of structures, to damage assessment and to the resulting consequences (economic losses, functional losses, and downtime).

The SimCenter welcomes collaboration with researchers committed to early-stage development to:

1. Articulate the required data and meta-data models.
2. Develop and evaluate computational workflows to link data sets and simulation software.
3. Conduct trial studies and evaluations.

Simulating Community Resilience

A major challenge addressed by the SimCenter is extending performance-based engineering tools to evaluate community-level resilience to natural hazards. The goal is to integrate data and models across geographically distributed lifeline systems, building inventories, and the socio-economic features of communities.

This involves extension of data and meta-data models of buildings, infrastructure components and infrastructure systems to include data compatible with geographic information systems that form the basis of urban planning tools and models.

To develop and explore these tools, the SimCenter is working with the open-source platform UrbanSim (http://www.urbansim.com/), which has a growing user base among urban planners. Testbed applications to integrate natural hazard information into UrbanSim are being explored in San Francisco and other U.S. cities.

Studies utilizing UrbanSim or other tools wherein data and metadata can be aggregated will enable diverse groups of researchers to carry out community/system resilience studies at network and regional levels. Tools that harvest data/metadata that can be used to build analysis models, and testbed studies that will utilize the SimCenter framework—which will enable its further development and refinement—are of particular interest.

Harnessing High Performance Computing for Natural Hazards Research and Engineering

Effective utilization of high performance computing is essential to achieve the envisioned outcomes for the NHERI program.

The SimCenter is collaborating closely with DesignSafe to develop workflow tools that can simplify and facilitate integration of databases, simulation software, and uncertainty quantification tools on multi-processor supercomputers, computing clusters, and cloud-based computing resources.

The SimCenter is collaborating with developers of the Pegasus workflow system (https:// pegasus.isi.edu/) to develop workflow tools that will allow express multi-step computational tasks across a range of computing environments from desktops to campus clusters, grids, and clouds.

Testbed studies involving large distributed systems (lifelines, transportation systems, etc.) or regions are needed to explore and quantify the scalability of cloud-based simulations capabilities that SimCenter framework will offer.

Empowering the Next Generation of Natural Hazards Researchers

Complementing the computational tool development, the SimCenter's education and outreach program is deploying educational software, webinars, and online resources to educate undergraduate and graduate students on the use of advanced computational methods for natural hazards research.

Where appropriate, the SimCenter will partner with DesignSafe and the NHERI Experimental Facilities to develop hands-on bootcamps and online programs to apply the simulation tools across all domains of NHERI. The SimCenter encourages NHERI researchers to utilize these tools, contribute content, and provide feedback.

Appendix B6: University of California at Davis Centrifuge Facility

EXPERIMENTAL FACILITY OVERVIEW

The 9-m and 1-m radius geotechnical centrifuges at the Center for Geotechnical Modeling (CGM) at UC Davis provide unique and versatile modeling capabilities for advancing our ability to predict and improve the performance of soil and soil-structure systems affected by earthquake, wave, wind and storm surge loadings.

Centrifuges enable the use of scale models to represent nonlinear, stress-dependent responses of soil masses that are many times larger than is possible on the world's largest 1-g shaking tables. The centrifuge facilities enable the building of basic science knowledge; the validation of advanced computational models from the component to holistic system level; and the validation of innovative mitigation strategies.

Additional information regarding the facility and leadership group is available at the DesignSafe website: https:// ucdavis. designsafe-ci.org.

RESEARCH OPPORTUNITIES

Complex Modeling with the 9-M Radius Centrifuge

The 9-m radius centrifuge, which has the largest radius of any centrifuge with a shake table worldwide, enables testing of physical models large enough to: (1) model holistic system levels of complexity and (2) obtain measurements of complex local mechanisms through inverse analyses of data from dense instrumentation arrays.

Models with holistic levels of complexity can produce one-of-a-kind measurements of:

- Non-linear dynamic multi-story structure soil-structure interactions with various shallow or deep foundation systems.
- Non-linear dynamic interactions between bridge approach embankments, piled abutments, and intermediate piers.
- Seismic demands on pipelines, underground structures, or tunnels, including uplift mechanisms where submerged and surrounded by liquefiable soils.
- Non-linear deformations and seismic performance of retaining structures, including mechanically stabilized earth retaining systems and quay walls.
- Seismic performance of structures and embankments supported on liquefiable or weak soil profiles remediated with geosynthetic drains, geosynthetic reinforcements, local densification techniques, soil-cement reinforcements, structural reinforcing elements, chemical grouting, or bio-mediated cementation or desaturation techniques.

Inverse analyses of data from dense instrumentation arrays in these large models can produce measurements from complex local mechanisms, such as:

- Dynamic soil-pile load-transfer (p-y) mechanisms in liquefying soil.
- Dynamic soil-pile-cap load transfer mechanisms in laterally spreading ground.
- Foundation rocking mechanisms for linear and nonlinear structures supported on shallow foundations or mixed foundation systems.
- Pore pressure diffusion and volumetric strain profiles leading to strain localizations (or water film formation) between liquefying sands and overlying clay layers.

Research possibilities using the 9-m radius centrifuge are as varied as the geotechnical and foundation systems encountered in practice and the ingenuity of our users, as evidenced by the ever broadening array of problems examined by current and past projects.

Exploration of New Ideas and Parametric Studies

The 1-m radius centrifuge, with its smaller models, provides for a high throughput of relatively simple (component) tests that enables efficient exploration of new ideas and rapid parametric studies. For example, the 1-m centrifuge has been used to demonstrate the use of bio-cementation to increase liquefaction resistance of sands and to examine the cyclic (quasi-static) rocking responses of single-footings by performing dozens of tests with varying soil types, footing geometries, and imposed axial, shear, and moment loadings. The 1-m centrifuge provides an effective and economical training ground for users to gain hands-on experience in centrifuge modeling prior to moving to test on the 9-m radius centrifuge.

The 9-m centrifuge enables holistic systems-level physical models; e.g., nonlinear multi-story structure-soil-structure interaction (top left insert) and multiple configurations of rocking foundation systems (lower left insert) (Photo: Ross Boulanger, UC Davis).

Validation of Advanced Computational Models

The 9-m and 1-m centrifuges provide a multi-faceted basis for validation of advanced computational models, which is an overarching challenge that will persist for some time due to the variety of multi-scale, multi-physics, coupled nonlinear interactions that come to the forefront in different realizations of natural, extreme hazards.

The physically large and densely instrumented experiments on the 9-m centrifuge enable validation against the complex local mechanisms defined through inverse analyses of dense instrumentation arrays, while the versatility of having both 9-m and 1-m centrifuges enables validation from component to holistic levels of system complexity.

A densely instrumented model of a pile group subjected to seismic, wind, or wave loading could provide multiple levels of data for validating computational models by comparing predicted and measured stress-strain responses in the soil, force transfer relationships for the piles (e.g., p-y and t-z behaviors), and pore pressure diffusion processes around the piles (local flow rates and volumetric strains), in addition to traditional comparisons of point measurements of accelerations, displacements, pore pressures, bending moments, and axial forces.

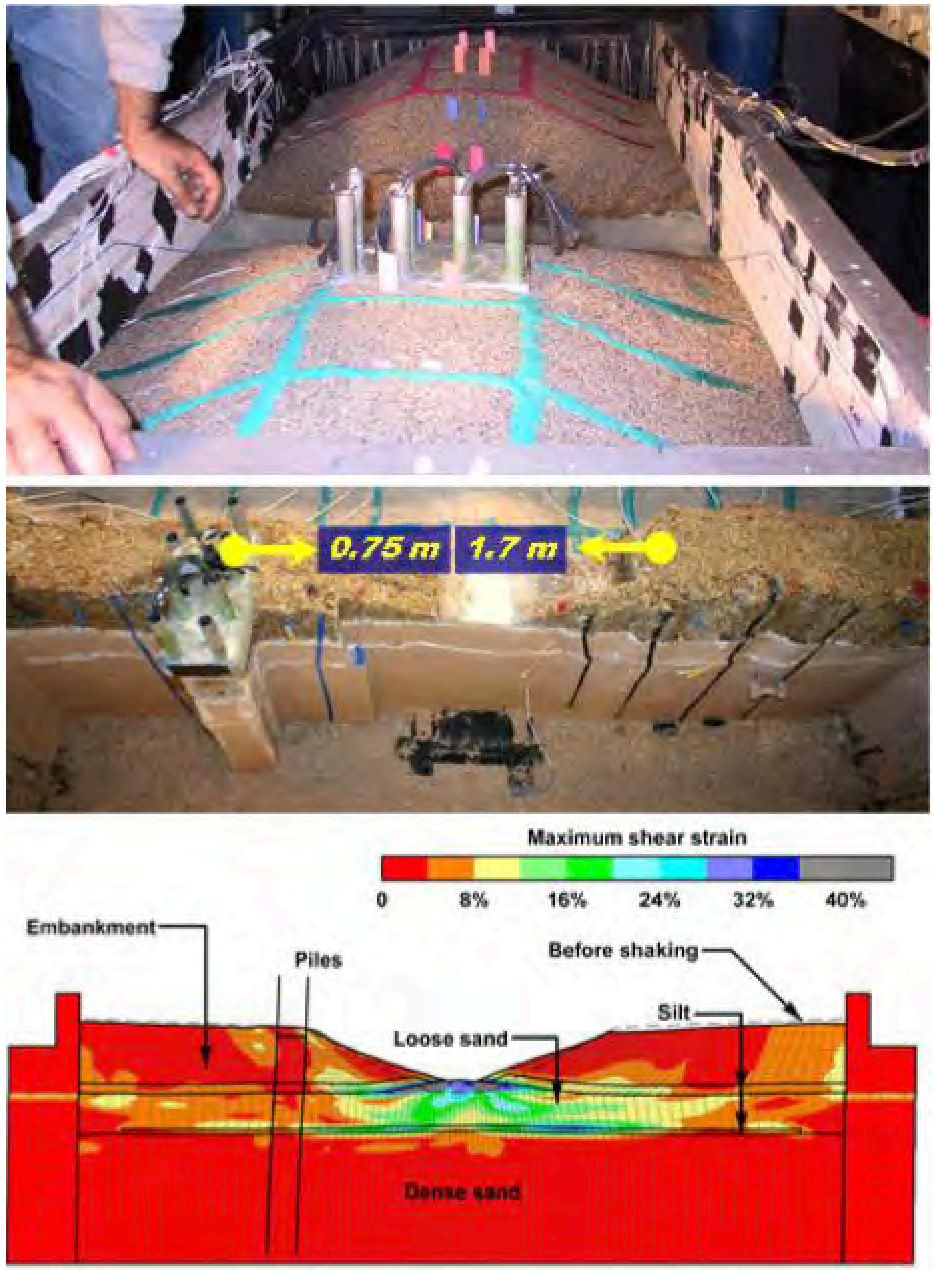
Validation against measurements of complex local mechanisms provides a higher-resolution evaluation of computation models, and can help identify computational modeling limitations that affect simulation accuracy and generalization at a global scale.

Seismic Response and Characterization of Challenging Soils

The 9-m and 1-m centrifuges also provide unique opportunities for developing and validating engineering procedures for determining, for a range of challenging soil types, the properties required for advanced computational models.

Determining soil properties for heterogeneous natural deposits or constructed fills across the scale of civil infrastructure systems usually involves a program of in-situ testing (destructive or nondestructive) and/or laboratory testing of field samples. All currently available in-situ tests, sampling tools, and laboratory tests have known limitations in certain types of soils.

Worse yet, there are a broad range of soil types for which no reliable in-situ test or sampling procedure has been developed, which makes the estimation of properties a dominant source of uncertainty in the application of advanced computational models. Examples include sensitive clays and silts (e.g., instabilities due to strain softening), gravelly and cobbly soils (e.g., particle size effects for in-situ tests and loading responses), intermediate soils (e.g., interpretation of in-situ test data in clayey sands to sandy silts), and finely inter-bedded sands and fine-grained soils (e.g., effect of inter-bedding on composite response, and lack of resolution in in-situ test data in thin layers).



A 9-m model of opposing bridge abutments with and without piles (top photo) provided experimental measurements of pile-pinning effects (excavated section in middle photo) for validation of computational models (bottom graphic) (Photo: Ross Boulanger, UC Davis).

Centrifuges provide opportunities to obtain inflight characterization tests (e.g., vane shear, T-bar, CPT, Vs, Vp, and samples for lab testing) and system performance data on the same experimental specimen. The 9-m centrifuge offers the greatest capability for performing these characterization tests in models with realistic holistic levels of system complexity (including geologic complexity, such as inter-bedded sand and silt deposits) and minimizing scale effects (e.g., distorted ratio of penetrometer size to particle or interlayer size). Smaller centrifuges could contribute as well, but their smaller sizes limit model complexity and increases scale effects for some soils and characterization tests. The largest 1-g soil boxes (e.g., at UCSD) could also contribute, but again they have limits on model complexity and the range of achievable overburden stresses.

Collaborative Opportunity
Combinations of experiments using the NHERI centrifuge facilities (UC Davis), mobile field dynamic shakers (UT Austin), and large 1-g soil box (UCSD) provide flexibility and potential synergy for enabling progress across many of the above challenges.

Response of Geotechnical Systems to Loadings from Earthquakes, Waves, Wind, and Storm
There are numerous other opportunities for technical breakthroughs on issues affecting specific geotechnical infrastructure systems under loadings from earthquakes, waves, wind, and storms.

Examples include the effects of ground deformations or erosion on underground pipelines, effects of tsunamis or storm surge on levees and foundations, effects of storms and earthquakes on foundation systems for near-shore and offshore wind turbines, and development of innovative, low-cost ground improvements for residential homes or levees where society requires a finer balance between costs and performance.

Collaborative Opportunity
A combination of NHERI facilities could be particularly effective for addressing some problems; e.g., the performance of near-shore wind turbines could be examined using model tests at the wind facilities to understand their dynamic responses, model tests at the centrifuge facilities to understand the performance of different foundation systems, and the mobile shakers to characterize the response characteristics of turbines in the field.

These and other pressing research needs offer opportunities for partnerships between industry, academia, and public agencies utilizing the centrifuge facilities in combination with other NHERI facilities (wind, tsunami, mobile shaker, 1-g shake table, and RAPID) to contribute to safer and better-managed civil infrastructure systems.

Appendix B7: University of California at San Diego Large High-Performance Outdoor Shake Table

EXPERIMENTAL FACILITY OVERVIEW

The large, high-performance outdoor shake table (LHPOST) at UC San Diego, with a steel platen that is 12.2 meters long by 7.6 meters wide, has performance characteristics that allow the accurate reproduction of near- and far-field earthquake ground motions in six degrees of freedom (DOFs).

The facility supports seismic testing of large/full-scale structural, nonstructural, geotechnical, and geostructural systems up to a weight of 20 MN. Two large soil boxes can be used in conjunction with the shake table to investigate the seismic response of soil-foundation-structural systems.

A reusable testbed building is available to enable low-cost testing of components and systems under simulated dynamic 3D loading, including but not limited to seismic protective systems, lateral force resisting systems, and nonstructural systems. Basic hardware and software are available to support real-time hybrid shake table testing. Systems tested at the facility can utilize extensive instrumentation and data acquisition capabilities, including a broad array of state-of-the-art and advanced analog sensors and high-definition video cameras, to support detailed monitoring of the system response through hundreds of data channels.

A reinforced concrete slab, 13.41 m by 9.14 m and 0.91 m thick, designed to resist heavy crane loads, was built near the shake table to serve as a staging area for the construction of small to moderate size specimens (up to a weight of 100 tons). This staging area increases the efficiency of the facility by allowing off-table construction of test specimens and/or subassemblies.

The NHERI shake table facility at UC San Diego is transforming seismic hazard mitigation research by enabling large/full-scale component and system tests under realistic earthquake loads that:

- Provide fundamental knowledge for understanding complete systems behavior during earthquakes, from initiation of damage to the onset of collapse, including the effects of soil-foundation-structure interaction and the contributions of lateral and gravity load-resisting systems and non-structural systems.
- Provide data for the development, calibration and validation of high-fidelity physics-based computational models of structural/geotechnical/soil-foundation-structural systems that will progressively shift the current reliance on physical testing to model-based simulation for the design and performance assessment of civil infrastructure systems subjected to earthquake hazards.
- Provide data and fragility information to support the development of simulation tools that can achieve the full realization of performance-based design, which has emerged as the most rational and scientific way to evaluate and reduce the risks of the civil infrastructure to natural and man-made hazards.
- Provide the ultimate validation tests for retrofit methods, protective systems, and the use of new materials, components, systems, and construction methods that can protect civil infrastructure systems against earthquake hazards.

Supporting Experimental Facility services include: Assistance in NSF research proposal development; test specimen design, construction and instrumentation; test protocols and software implementation; operating the shake table; high definition video recording; data acquisition, processing, archiving and curation; safety and user training.

Additional information regarding the facility and leadership team is available at the DesignSafe website: https://ucsd.designsafe-ci.org.

EXAMPLES OF RESEARCH POSSIBILITIES

Performance in Future Earthquakes of Existing Older (Wood, Concrete, Masonry, and Steel) Buildings, Which Were Not Designed and Constructed According to Current Codes and Construction Practice

Preservation of existing civil infrastructure systems is essential to attaining disaster resilience and sustainability. Past earthquake events in the U.S. and around the world repeatedly demonstrated that the vast majority of structural collapses in any seismic event have been associated with older structures.

Factors leading to such poor performance include inadequate load transfer mechanisms, low-quality materials, inadequate connection details, limited ductility of structural elements, excessive interaction between structural and non-structural elements, and limited system redundancy. The development of adequate databases and reliable computational tools to evaluate the earthquake performance of these older structures so as to accurately identify the "killer" structures is of critical importance to ensuring life safety and disaster-resilient communities.

Collaborative Opportunity
This research topic lends itself to collaboration with the Lehigh University Experimental Facility.

Resilience-based seismic design methodology for tall wood buildings (Photo: NHERI@UC San Diego).

Advancing Research and Raising Awareness for Earthquake Resilient Communities

The Large High Performance Outdoor Shake Table at the University of California, San Diego, is the nation's largest earthquake simulator facility capable of subjecting large scale models of buildings, bridges and other critical infrastructure including the supporting soil to realistic earthquake motions.

The landmark seismic experiments conducted at this national shared use facility are providing data essential to advance the science, technology and practice of earthquake engineering. Seismic design codes and standards have been updated based on observations and results obtained from life size experiments.

Full-scale structural and nonstructural building system subjected to seismic loading (Photo: NHERI@UC San Diego).

Effectiveness of New and Existing Seismic Retrofit and Mitigation Techniques and Post-Earthquake Repair Methods for Building Structures and Critical Facilities
Identifying and improving the effectiveness of economical seismic retrofit methods will encourage building and facility owners to adopt such measures and upgrade deficient structures to meet current safety standards.

The performance of a retrofitted structure is often governed by the interaction and connectivity of new and existing materials and components in the system. This often presents a challenge in computational modeling.

Sometimes, localized retrofit or strengthening of structural elements produces unexpected behavioral outcomes at the system level. Hence, system-level testing provides the ultimate assurance of the effectiveness of these measures. The actual seismic performance of structural systems designed according to current code standards has not been verified. Can their damage and failure mechanisms be reliably predicted? Do they have an acceptable margin of safety against collapse? Current seismic design standards are largely based on data obtained from quasi-static, in-plane testing of structural components.

While such data are crucial for the development of design and detailing requirements to ensure the ductile behavior of structural members, the actual performance of a building in an earthquake is highly dependent on how these components are proportioned, connected, and interact with each other as a system under multiple components of excitation. This may be due to varying boundary conditions, combined stresses from multiple load components, and/or interaction with other structural or nonstructural components.

The next-generation performance-based design (PBD) code provisions will focus on the system-level performance as predicted by computational simulation models, which have to be calibrated with available experimental data. Testing large-scale structural and SFS systems will provide critically needed data to assess how existing code provisions measure up to new performance criteria and to calibrate computational simulation models.

Laminar soil shear box on shake table (Photo: NHERI@UC San Diego).

Collaborative Opportunity
This research topic lends itself to collaboration with the Lehigh University Experimental Facility.

Effects of Soil-Foundation-Structure Interaction (SFSI) on the Performance of Structural Systems
SFSI can be beneficial or detrimental to the performance of structures during earthquakes. Design guidelines considering these effects are mostly based on analytical models, computational simulations, small-scale shake-table experiments in centrifuges, large-scale field testing of pile and slab foundations, and field observations from past earthquake events.

Large-scale field testing provides pertinent data to calibrate soil properties in analytical and computational models; however, it cannot conclusively validate how SFSI affects structural response during an earthquake, because these tests neglect the dynamics of soil response during earthquake shaking and the inertial interaction with the superstructure.

Moreover, they are generally at amplitudes lower than design target earthquake demands. The scale of soil-foundation-structural specimens in centrifuge tests has to be necessarily very small. This means that detailing of superstructure elements and materials for these tests necessitates simplicity due to the small scale. Therefore, results of such tests will have limited accuracy regarding the behavior of the actual structure or foundation.

Shake-table tests used in combination with large soil boxes and reasonable size foundation and structural models are needed to complement centrifuge tests to validate corresponding computational models. The 6-DOF LHPOST is ideally suited for experimental investigations of dynamic SFSI effects including the additional rocking and torsional components of motion generated at the foundation by the inertial interaction with the superstructure. These types of tests can also be used to study the performance of underground structures, bridge abutments, earth retaining walls and slope stability in hillside construction.

Collaborative Opportunity
This research topic lends itself to collaboration with the UC Davis Experimental Facility.

Ability of Innovative Structural Systems, Materials, Construction Methods, Design Concepts, and Response Modification Devices to Deliver Their Targeted System-Level Performance
Through years of research, current seismic design and construction standards more or less satisfy the life-safety design criterion. To move towards a sustainable and disaster-resilient community, methods and techniques to minimize structural and non-structural damage, post-earthquake downtime and repair cost, and the total economic loss in an earthquake event have received much attention.

These include the development of sustainable and high-performance materials, innovative structural configurations, and effective earthquake protection technologies including seismic isolation, rocking foundations and inertial force-limiting floor systems. There also exists tremendous potential to transform the construction process of civil infrastructure using modern fabrication technologies. For example, borrowed from the field of rapid prototyping, it is now possible to use 3-dimensional printing together with sustainable rapid-set cementitious materials to accelerate the construction process. System-level testing provides the ultimate evaluation of these concepts, which can lead to new breakthroughs in structural engineering and earthquake hazard protection.

Collaborative Opportunity
This research topic lends itself to collaboration with the Lehigh University Experimental Facility.

Impacts of Nonstructural Components on Overall Losses in Earthquakes and Strategies to Minimize these Losses
Damage to architectural elements, mechanical/electrical/ plumbing systems, and building contents, often collectively referred to as nonstructural components and systems (NCSs), can incur significant direct and indirect economic losses in the event of an earthquake. Repair and replacement costs can be significant and the temporary loss of functionality of critical facilities like hospitals is not only costly but also has direct and indirect impacts on life safety.

Moreover, to support safe evacuation and post-event rescue, it is absolutely essential that some of these systems, such as those supporting egress, remain operable following an earthquake.

NCSs have become an important consideration in the next-generation PBD methodology. Understanding how non-structural components respond and interact with the structural system and devising effective means to protect them from damage are essential. Knowledge has been limited due to the paucity of full-scale building shake table tests under multi-directional earthquake excitation that incorporated NCSs. The LHPOST can support system-level studies with realistic structures and realistic earthquake excitations on total structural systems (structures that house NCSs). Data from these studies can be used to derive fragility functions for PBD.

Effects of Rotational Components of Earthquake Ground Motions
Dynamic seismic response analyses of systems for either design or evaluation purposes commonly ignore the rotational components of earthquake ground motions. This has been a widely accepted practice in the earthquake engineering community due to (i) the lack of recorded rotational ground motions during strong earthquakes and (ii) a common assumption in the seismological community that rotational components are small enough to be neglected. In past earthquakes, structural failures and damage have been linked to rotational and differential ground motions including torsional response.

Numerical studies also indicate that rotational ground motions can significantly affect structural response and the need to better understand these effects on tall buildings and other structures.

Appendix B8: University of Colorado CONVERGE

FACILITY OVERVIEW

CONVERGE advances disciplinary and interdisciplinary hazards and disaster research and establishes and strengthens extreme events research coordination networks. The mission of CONVERGE is to:

- Identify and coordinate social science and engineering researchers and interdisciplinary research teams before, during, and after disaster.
- Advance the ethical conduct and scientific rigor of rapid response disaster research.
- Support the training and mentoring of a diverse next generation of hazards and disaster researchers.
- Fund virtual reconnaissance, field research, and the development of novel research instruments and data collection protocols.
- Accelerate the development of mobile applications for hazards and disaster research through a partnership with NSF-NHERI RAPID.
- Encourage the publication of data and data collection instruments and protocols through a partnership with NSF-NHERI DesignSafe.

RESEARCH NETWORKS AND POSSIBILITIES

CONVERGE Leadership Corps

One of the central tasks of the CONVERGE initiative is to create and support the first-ever Leadership Corps for natural hazards research. The Leadership Corps includes the principal investigators of the NSF-supported Extreme Events Research and Reconnaissance (EER) networks (GEER, SSEER, StEER, NEER, OSEEER, and ISEEER) and the leaders of NHERI Network Coordinating Office, RAPID Reconnaissance Facility, DesignSafe, and CONVERGE.

There are many well-established networks doing important work in the natural hazards reconnaissance space. The CONVERGE Leadership Corps, however, is dedicated to linking the National Science Foundation-supported EERs and the NSF-NHERI components that facilitate and advance the work of the natural hazards reconnaissance community.

In the next five years, the CONVERGE Leadership Corps will:

- Develop an internal operations manual to clarify how the principal investigators of the various NSF-supported EERs and NHERI components will work together during a major disaster.
- Develop an outward-facing research response plan to support the coordination of research teams and clarify the ways that researchers can effectively interface with local, state, and federal authorities; industry partners; and the non-profit sector.
- Develop best practice guidance for rapid response disaster research by publishing the CONVERGE Briefing Sheets series, in partnership with the Natural Hazards Review.
- Write a science plan to inform future rapid response disaster research investigations.
- Assume shared responsibility for internal and external messaging and communications during rapid response disaster research missions involving large numbers of engineers and social scientists.

RESEARCH RESOURCES: TRAINING AND GUIDANCE

Part of the mission of CONVERGE is to accelerate the training and mentoring of a diverse next generation of hazards and disaster researchers. The CONVERGE facility is developing free, online training modules and a series of briefing sheets and check sheets for rapid response disaster research.

CONVERGE Training Modules

These modules are designed to advance social science, engineering, and interdisciplinary hazards and disaster education. The information in these modules is designed to accelerate the training of hazards and disaster researchers, with a special emphasis on students, emerging researchers, situational researchers, and those interested in joining or leading interdisciplinary teams.

The training modules cover a wide range of rapid response research topics. These modules are meant to help prepare individual researchers and interdisciplinary teams to carry out extreme events research that is coordinated, comprehensive, coherent, ethically grounded, methodologically sound, and scientifically rigorous.

The first training module, Social Vulnerability and Disasters, is now available. Soon to be released training modules focus on a wide range of additional topics including, for example, cultural competence in hazards and disaster research, disaster mental health, conducting emotionally challenging research, and IRB procedures for human subjects research. Each module features learning objectives, lesson plans, written content, and case study vignettes. The module also includes a list of publications for further reading as well as access to related standardized scales and measures, online resources, data sets, and other information. Each module is followed by a short multiple choice quiz. Those who receive a score of 80% or higher will receive a CONVERGE Training Module Certificate of Completion.

CONVERGE Disaster Research Briefing Sheets Series

Rapid response research has the potential to illuminate root causes of disasters and the consequences of their impacts on human and built environments. Understanding the complexities of extreme events requires researchers to be well trained in the history, ethics, and practice of quick response research. The CONVERGE Disaster Research Briefing Sheets Series is designed to provide background and context for the hazards and disaster social science, engineering, natural science, and interdisciplinary research communities in these important concepts.

This special peer-reviewed series will be published in partnership with the journal Natural Hazards Review and will be guided by members of the CONVERGE Leadership Corps.

CONVERGE Disaster Research Check Sheets

As a supplement to the CONVERGE Disaster Research Briefing Sheets Series, the CONVERGE team has developed a series of short, graphical check sheets meant to be used as researchers design their studies, prepare to enter the field, conduct quick response field research, and exit the field. The series, which is currently in development, will offer best practices for disaster research and consist of 1-2 page check sheets.

Mobile Data Collection:
Collaboration with the RAPID Facility

The RAPID facility provides researchers with equipment, software, and training and other support services needed to collect, process, and analyze perishable data from natural hazards events.

Since its launch in 2017, over 170 researchers have taken part in RAPID training sessions, and more than 55 researchers have used equipment from the facility to support novel natural hazards research.

The RAPID research and development teams have partnered with the our team at CONVERGE to advance the RAPID App (RApp), which is a mobile application to support the ethical and secure collection of quantitative, qualitative, and mixed methods hazards and disaster research data.

The RAPID and CONVERGE teams are working together to make it possible for social and behavioral scientists to use the RApp to collect survey data (through uploading new instruments and using existing scales and measures) and to record interview and observational data while in the field.

RApp will also include field manuals and damage assessment protocols and will link directly to the NSF-NHERI DesignSafe Cyberinfrastructure, allowing researchers to upload and save their field data securely via our jointly produced Field Research data model. An initial version of RApp is currently pre-loaded on 15 iPads, which are available to be checked out via the RAPID facility. In the near future, RApp will be free to download.

Data Publication: Partnership with DesignSafe-Cyberinfrastructure and the RAPID Facility

As described previously in this appendix, DesignSafe is the web-based cyberinfrastructure platform for the NSF-NHERI network. Headquartered at the University of Texas-Austin, DesignSafe provides a secure data repository and the computational tools needed to manage, analyze, and publish critical data for natural hazards research. The DesignSafe cyberinfrastructure supports cloud-based research workflows, data analysis, and visualization.

Since its launch in 2015, over 3,000 researchers—predominantly from engineering—have taken advantage of DesignSafe functionalities, publishing almost nine terabytes of data across more than 100 datasets.

The DesignSafe research and development team has partnered with our CONVERGE facility and the RAPID facility, headquartered at the University of Washington, to develop a novel social science and interdisciplinary data model for natural hazards research. This data model—which will be released by February 2020—will, for the first time, allow social and behavioral scientists and members of interdisciplinary teams to publish legacy datasets as well as new qualitative, quantitative, and mixed methods field research data specific to hazards and disaster research. In addition, the data model is robust enough for researchers to publish data collection protocols, research instruments, and Institutional Review Board (IRB) protocols.

Through expanding the potential for researchers to have a Digital Object Identifier (DOI) assigned to their datasets and data collection protocols, the vision is to advance the possibility for richer collaboration and more cross-geographic site, cross-disciplinary, and cross-hazards replication within the disaster social science and engineering fields.

For more information, visit: https://converge.colorado.edu/.

Researchers at North Carolina State University participated in the recent CONVERGE training module demonstration webinar (Photo: Olivia Vila).

Appendix B9: University of Florida Wind Experimental Facility

EXPERIMENTAL FACILITY OVERVIEW

This Experimental Facility supports five major experimental resources:

1. Self-Configuring Boundary Layer Wind Tunnel (BLWT)

The BLWT simulates the first few hundred meters of the earth's atmosphere at reduced geometric scale on the order of 1:25 - 1:400. Air is forced through a large duct with an artificially roughened floor that imparts the surface drag caused by buildings, trees and other elements in the Earth's landscape.

The geometric dimensions and configuration of roughness elements in the upwind section are calibrated to effect desired approach flow conditions. Trips, spires or strakes are installed upwind of the roughness elements to introduce large-scale motions and to promote mixing. The roughness elements generate mechanical turbulence and induce boundary layer growth.

Similarity requirements include the mean velocity and turbulence intensity profiles, power spectra and integral length scales. A geometrically scaled model of the test subject installed on a turntable downwind is instrumented to record pressure, acceleration, displacement or base reaction data. Models can be manufactured using onsite 3D printers.

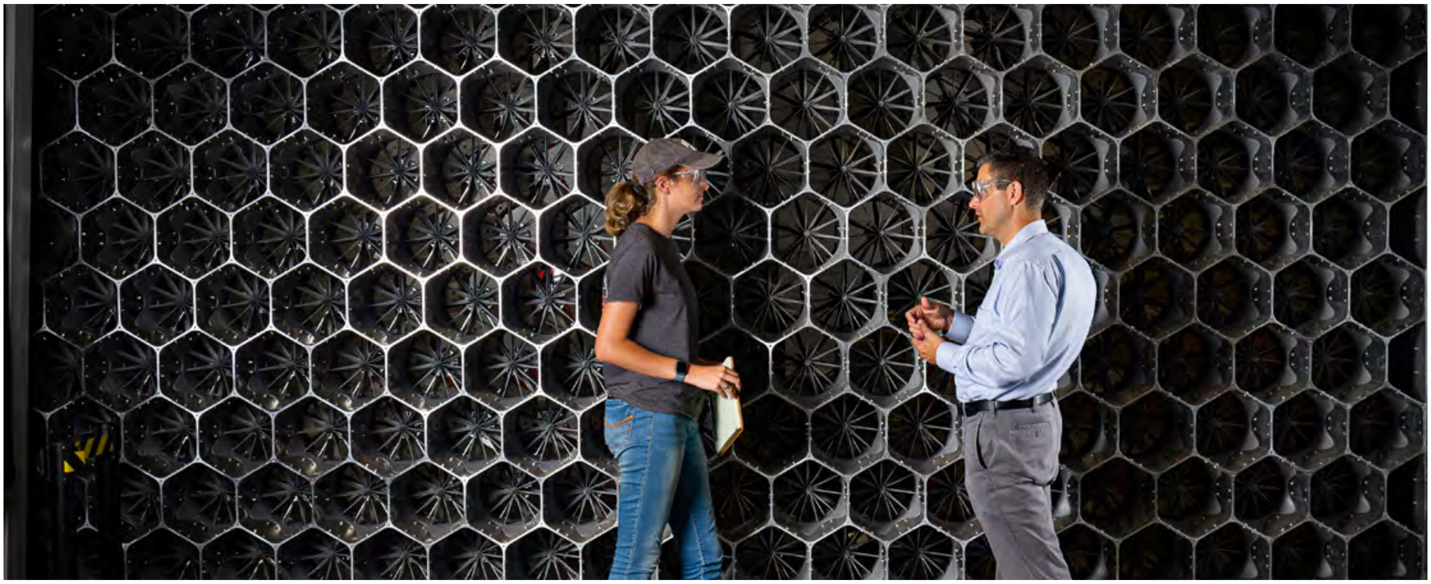
2. Multi-Axial Wind Load System (MAWLS)

The MAWLS is a unique large-scale dynamic wind effects simulator that imposes dynamic wind pressure in combination with static in-plane shear or uplift forces.

The system was designed to accommodate walls, components or cladding specimens up to 5.5 m by 7.3 m. The system is based on the pressure-loading actuator concept originally developed by the Building Research Establishment and later improved upon by the University of Western Ontario.

The system provides a means to replicate naturally occurring dynamic wind and pressure in a controlled laboratory environment. The MAWLS is composed of four principle components: fans, ducting, a control system, and the pressure chamber. The fan is a centrifugal blower with maximum pressure of 22 kPa at an airflow rate of 2,832 m3/min (100,000 CFM) and is powered by a 1818 HP at 1750 rpm power unit.

Five dampers comprise the control system: four butterfly dampers and a custom-built fast-acting opposed-blade louver damper. The four butterfly dampers change the flow configuration so that pressure or suction can be applied to the specimen, or alternatively bypass the chamber to drive air through a high-speed wind tunnel section (e.g. the DFS described in the next section).



The Flow Field Modulator uses 319 fans to vary the wind field in both time and space to simulate nonstationary wind events for boundary layer wind tunnel modeling. (Photo: Bernard Brzezinski, University of Florida).

When positive pressure is desired, the valves can be set to drive air into the pressure chamber. The valves also may be arranged to create suction in the pressure chamber. Placing seals between the specimen edges and pressure chamber maintain the air-tightness of the pressure chamber. Seals are fit around the supports, which can be adjusted to induce either one-way or two-way bending.

The high capacity of the system ensures that a fast response time will be maintained even if there is minor air leakage through or around the specimen. Dynamic fluctuation in air pressure is created by the louver damper, which rapidly changes the airflow in/out of the pressure chamber. A low range wet/wet differential pressure transducer is mounted in the pressure chamber to constantly measure pressure for feedback loop processing.

To conduct a test, the specimen is mounted in the reaction frame that is secured to the open side of the pressure chamber. The primary frame, fabricated from HSS shapes, is mounted to the face of the pressure chamber. It resists catenary or arching forces developed when the test specimen is subjected to loading and can also be used to apply in-plane loads to simulate shear or uplift. The frame capacity is 150 kN/m (10 kip/ft.) applied either horizontally or vertically. The primary frame is permanently attached to the pressure chamber, while the secondary reaction frames can be removed and resized to accommodate the dimensions of the specimen. Three Enerpac 30-ton actuators apply force to the top of the specimen through a loading head.

3. Dynamic Flow Simulator (DFS)

The DFS is used to determine ultimate wind uplift capacities of full-scale discontinuous roofing system specimens (tiles, asphalt- or metal-shingle systems), for which the uplift capacity is dependent on the geometric profile and the air permeability. The unique features of the DFS are the ability to replicate dynamic waveforms. Test specimens inside the DFS are subjected to the mean and turbulent components of near-roof wind, providing a unique tool to accurately measure the wind load and resistance of discontinuous roofing systems. The BLWT pressure-scanning system is used to measure pressures. Models can be manufactured using onsite 3D printers.

4. High Airflow Pressure Loading Actuator (HAPLA)

The HAPLA is ideally suited to conduct testing on wall materials and construction in wood, masonry, and aluminum-glass curtain walls and fenestration.

Conceptually based upon the University of Western Ontario-designed pressure-loading actuators, the HAPLA was designed to test highly air-porous systems and wall systems that progressively fail during testing.

The HAPLA can be used to study (a) through-soffit wind-driven rain effects in residential attics; (b) effects of weathering and aging on structural performance of wall or cladding systems; (c) structural load path at residential building corner walls; (d) validation of standard test protocols against realistic simulations of wind and wind-driven rain; and (e) fenestration performance.

The HAPLA consists of two 75 HP centrifugal fans that operate in series. A closed-loop air valve controls chamber pressure by modulating the amount of air traveling from the test chamber to the exhaust port. This design enables the HAPLA to test components under simultaneous fluctuating pressure up to 6 kPa under minimal leakage conditions.

A variable intensity water spray system (VIWSS) was developed to simulate wind-driven rain effects on building envelope systems. The VIWSS is installed within the steel chamber and consists of 25 nozzles. Wetting rates are adjustable from 50 mm/hr to 550 mm/hr. This large wetting range is required because rain deposition on a building façade is a function of the (nominal) product of the horizontal rainfall intensity (i.e. the flux of rain toward to the ground) and the wind speed.

5. Spatiotemporal Pressure Loading Actuator (SPLA)

The Spatiotemporal Pressure Loading Actuator (SPLA) is a similar instrument to the MAWLS and HAPLA, but is an array of four independent Pressure Load Actuators (PLAs) which can be simultaneously controlled to apply independent pressure traces on separate regions of a single test specimen. In contrast to industry-accepted test protocols, the SPLA can more realistically simulate both the spatial and time-varying pressures on building surfaces that cause elements like roofing systems and wall siding to fail.

The key features of the SPLA design are that it a) produces wind loads up to a Category 5 Hurricane (i.e. +7 kPa to -7 kPa range; b) can follow a pressure trace with high accuracy; c) has a frequency response of up to of 3 Hz; and d) can operate with substantial air leakage through cracks in the building materials. The SPLA uses a large re-configurable test bed that can be operated in vertical or horizontal orientations to more closely approximate the spatially correlated pressure fluctuations over large roof surfaces.

Additional information regarding the facility and leadership group is available at the DesignSafe website: https://ufl.designsafe-ci.org.

RESEARCH OPPORTUNITIES

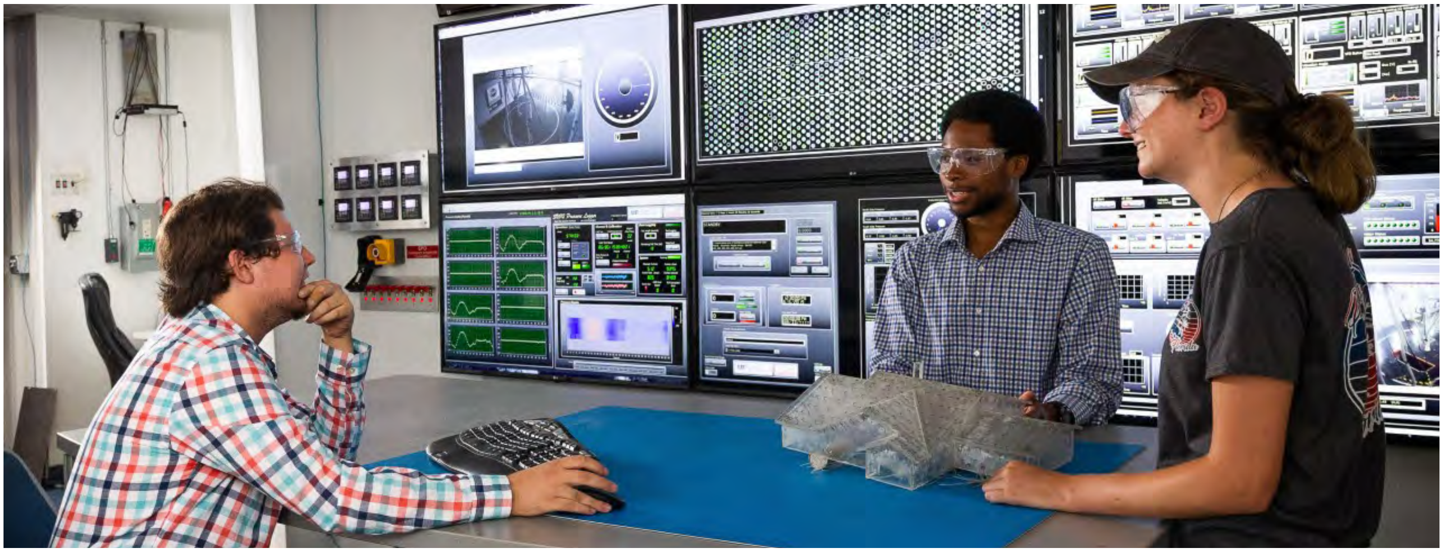
This Experimental Facility is available for the following key NHERI five-year research topics:

Boundary layer wind tunnel

- Cyberphysical testing of rigid and aeroelastic models, including buildings, bridges and other structures.
- Shape, mass, damping and stiffness optimization of civil structures and lifelines.
- Characterization of pressure coefficient fields on bluff-bodies for highly discretized ranges of aerodynamic roughness length or turbulence intensities.
- Characterization of wind-induced base shear and moment reactions using a high-frequency force balance.
- Modeling higher-order wind and pressure descriptors that are sensitive to small changes in approach flow.
- Testing and refinement of UAV control algorithms in highly dynamic wind conditions (e.g. damage inspections, first-response search efforts, pollutant dispersion sampling, etc.).
- Generation of time-varying loads to command hybrid testing systems, e.g., ATLSS at Lehigh University, MAWLS, HAPLA, SPLA.
- Input generation and validation of CFD and FSI modeling.
- Future: simulation of nonstationary winds and non-neutral velocity profiles.

Destructive Testing Equipment (HAPLA, SPLA, MAWIS, DFS)

- Cyberphysical testing of full-scale wall components and building systems.
- Performance-based design of partial mockups, components, and cladding for low-rise building systems, applying dynamic wind pressure and time-varying wind-driven rain (wetting) conditions.
- Characterization of the behavior and failure mechanisms of continuous and discontinuous roofing systems.
- Comparison of performance between conventional (human-built) construction and advanced approaches that apply additive manufacturing, prefabrication or robotics.
- Bridging ASTM and other test protocols to expected performance and failure thresholds under realistic dynamic extreme wind loading — i.e. advance pass/fail criteria to a rating-scale referenced to wind intensity.



Engineering students discussing ongoing projects in the University of Florida Boundary Layer Wind Tunnel Control Room (Photo: Bernard Brzezinski, University of Florida).

Appendix B10: University of Texas at Austin Cyberinfrastructure -- DesignSafe

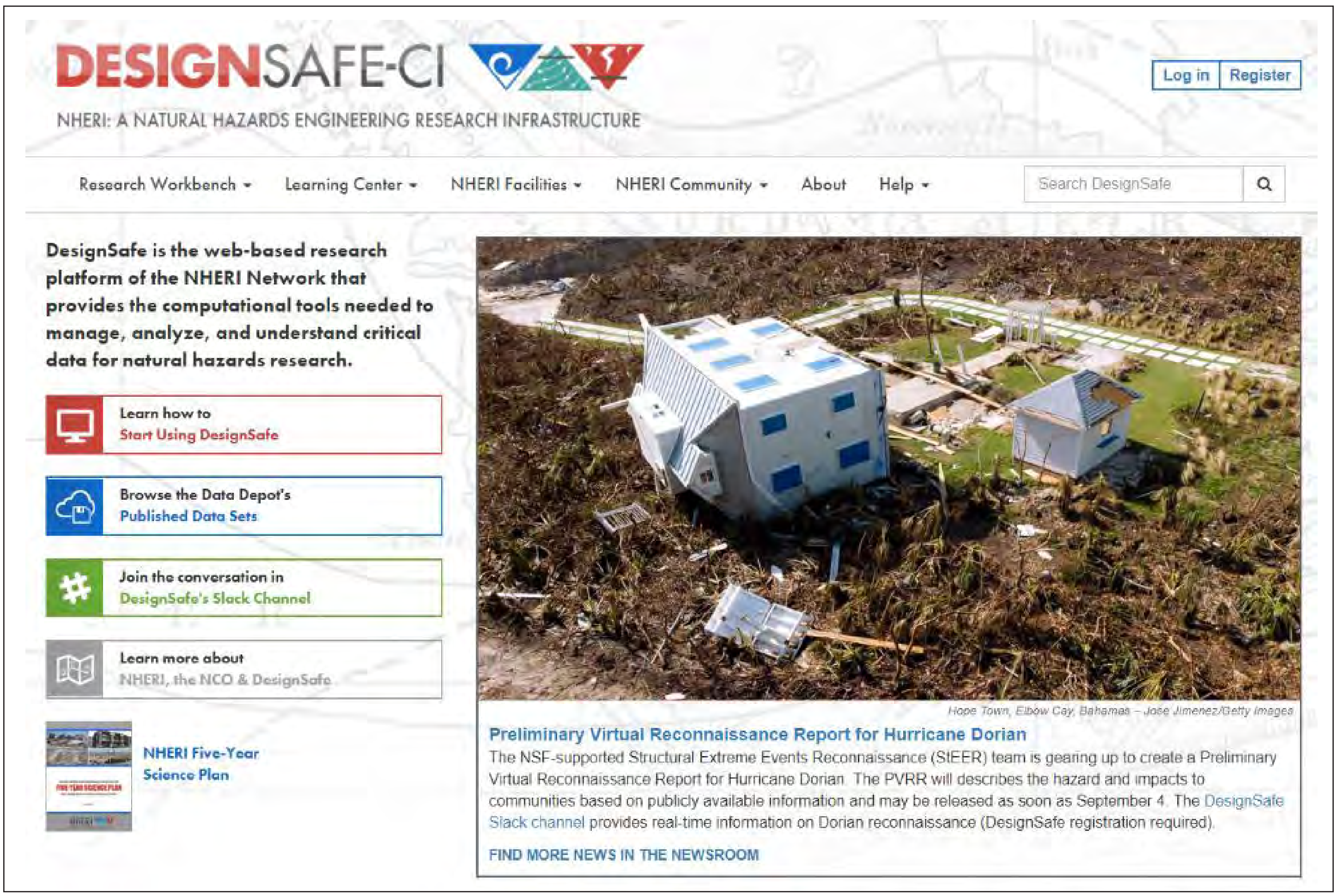
FACILITY OVERVIEW

The DesignSafe cyberinfrastructure (designsafe-ci.org/) has been developed as part of NHERI to facilitate transformative research that integrates experimental and field data, computational simulation, and large-scale data analytics to ensure our infrastructure and communities are safe from natural hazards.

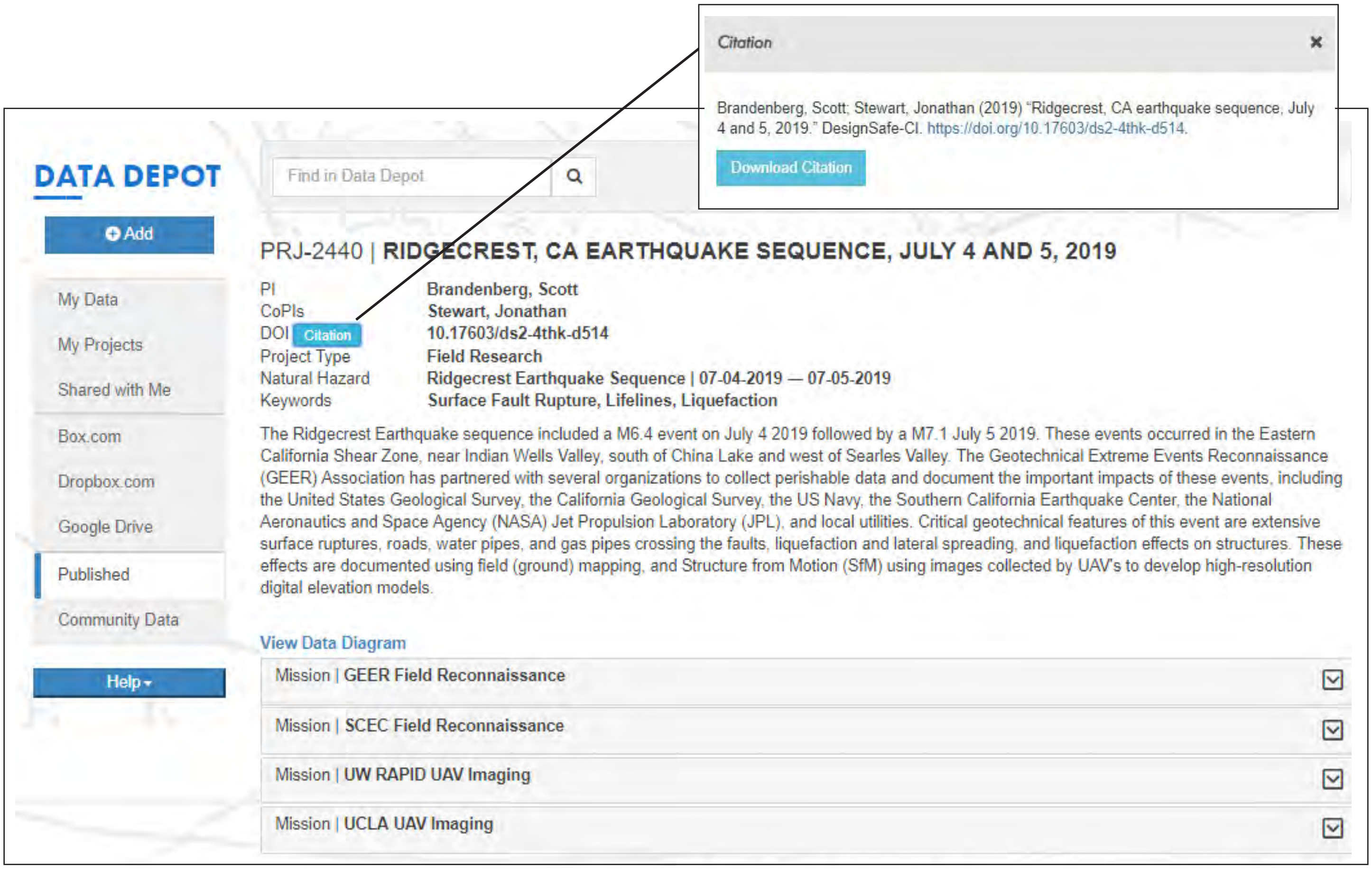
DesignSafe enables researchers to more effectively share, find, and analyze data; perform numerical simulations and utilize high performance computing (HPC); and integrate diverse datasets. These functionalities allow researchers to answer questions and make discoveries that they could not before.

The DesignSafe web portal includes the following components:

- The Research Workbench with access to the:
  - Data Depot data repository.
  - Discovery Workspace with simulation, data analytics, and visualization tools.
  - Reconnaissance Portal with easy access to field data obtained after natural hazard events.
- The Learning Center with webinars and other training materials.
- The NHERI Facilities with information on all NHERI components.
- The NHERI Community with various information for the natural hazards community.



DesignSafe Web Portal



Published Dataset with Citation Language and DOI.

Data Depot

At the heart of the cyberinfrastructure, the Data Depot (designsafe-ci.org/data) is the central data repository that supports users throughout the research lifecycle, from data creation to analysis to curation and publication.

Within the DesignSafe Data Depot, researchers have access to a private ***"My Data"*** space, a collaborative ***"My Projects"*** space, a ***"Community Data"*** space for publicly available, uncurated datasets, and a ***"Published"*** space for publicly available, curated datasets.

The ***Projects*** interface within ***"My Projects"*** represents the shared file system that can be used throughout a research project to share files and results with team members/collaborators who have been given access to the Project.

The Working Directory within a Project simply includes the folders and files uploaded to a project, and all research data collected as part of a research project, as well as processing scripts, data analysis products, and simulation models/results, can be deposited here starting from the inception of the project.

These data are kept private within a Project until curated and published by the research team. Using a Project to share data with your team members during the course of a project facilitates the progressive curation of data and eventual publishing.

End-to-end data management is provided within a Project through the Curation Directory. Here, researchers organize their data within one of the five available data models (Experimental, Simulation, Hybrid Simulation, Field Research, and Other).

These data models can support any type of research data, from heavily instrumented laboratory experiments, to large-scale computational simulations, to field observations after natural hazard events, to social science survey instruments/results, and more. On-demand assistance from a curator is available to provide training and to guide researchers through the use of the data curation tools.

After organizing the data within the selected data model, a publication preview is provided to the researcher and ultimately the data is published within the "Published" section of the Data Depot with a Digital Object Identifier (DOI) and full citation language. This citation language allows researchers and colleagues to formally cite the data within the references sections of any paper that uses the data.

Discovery Workspace

The Discovery Workspace (designsafe-ci.org/rw/workspace) provides access to a suite of tools that support computational simulation, data analytics, and visualization. Many of these tools make use of the high performance computing (HPC) systems at the Texas Advanced Computing Center (TACC). Most tools are open source, but some commercial tools require that you "bring-your-own-license". Currently available tools are listed below, but note that tools are continuously being added to the Workspace.

Select Tools Available in the Discovery Workspace

- ADCIRC, ADCIRC + SWAN
- LS-Dyna, LS-PrePost
- Paraview
- OpenSees
- Jupyter
- QGIS
- OpenFOAM
- Matlab
- Potree Converter/Viewer

Many of these tools are also available at the command line, but a formal HPC allocation at TACC is required to access the command line (designsafe-ci.org/rw/user-guides/allocations-policy/). If a tool needed for your research is not available in DesignSafe, please contact us via help@designsafe-ci.org to discuss making it available.

Reconnaissance Portal

The Reconnaissance Portal (designsafe-ci.org/recon-portal/) provides an access point to data collected during post-event reconnaissance of hurricane, earthquake, tornado, tsunami, and other natural hazard events.

These data may be collected by the NHERI RAPID facility, its users, or other researchers participating in reconnaissance through organizations such the NSF-supported extreme events reconnaissance networks and CONVERGE (designsafe-ci.org/facilities/converge/).

Natural hazard events for which data are available are indicated on the main map interface of the Reconnaissance Portal, and selecting an event exposes the available datasets. These datasets may be located in the DesignSafe Data Depot, or may be located through an external website or data repository. The datasets found in the Data Depot are accessible by analytics and visualization tools in the Discovery Workspace.

Reconnaissance activities produce diverse types of data, including civil infrastructure performance data (e.g., damage estimates, ground movements, coastal erosion, wind field estimates), remotely sensed data (e.g., photos, video, LIDAR point clouds, satellite imagery data), or human experiential data (e.g., social media data, societal impact data, survey or interview data).

Several tools are available in the Workspace to specifically support the exploration of reconnaissance data. HazMapper provides a simple mapping interface to integrate GPS track logs, geo-tagged photos, and other geo-located data.

DesignSafe Reconnaissance Portal

The Potree viewer provides a simple interface to view, measure, and analyze three-dimensional point cloud data within a web-browser. Additionally, DesignSafe integrates seamlessly with the RAPID facility's RApp mobile app, which allows data collected with RApp to be automatically uploaded to a selected DesignSafe project once the mobile device is connected to the internet.

Learning Center

DesignSafe's Learning Center (designsafe-ci.org/learning-center) hosts an ongoing series of webinars for learning about natural hazards research — from software tutorials to research case studies. Tutorials are archived on the DesignSafe YouTube Channel under the Tutorials playlist.

Appendix B11: University of Texas at Austin Large Mobile Shakers

EXPERIMENTAL FACILITY OVERVIEW

The NHERI@UTexas Experimental Facility contributes unique, literally one-of-a-kind, large, mobile dynamic shakers and associated instrumentation to the study and development of novel, in-situ testing methods that can be used to both evaluate the needs of existing civil infrastructure and optimize the design of future civil infrastructure, such that our communities become more resilient to earthquakes and other natural hazards.

The NHERI@UTexas equipment resources were primarily established with funding from the National Science Foundation (NSF) under the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) program. This equipment includes:

1. Five, large, dynamic shakers that can be used as mobile, wide-band dynamic sources for excitation of geotechnical and structural systems.
2. A tractor-trailer rig used to transport the four largest shakers.
3. A field supply truck for refueling and field maintenance of the mobile shakers.
4. An instrumentation van that houses state-of-the-art data acquisition systems and electrical power generation capabilities.
5. A field instrumentation trailer that has air-conditioned work space and electrical power generation capabilities.
6. An extensive collection of field instrumentation, DAC systems and a wide range of numerous sensors that are used to measure vibrational motions and pore water pressures.

Additional information regarding the facility and leadership group is available at the DesignSafe website: utexas.designsafe-ci.org.

RESEARCH OPPORTUNITIES

Characterizing the Nonlinear Dynamic Response and Liquefaction Resistance of Complex Geomaterials In Situ

In 2010-2011, the city of Christchurch, New Zealand was devastated by a series of powerful earthquakes.

The seismic demands imposed on the civil infrastructure at many locations in the city were higher than engineering design levels, causing severe structural damage and collapse, especially within the central business district (CBD). Ultimately, the Christchurch Earthquake resulted in 181 casualties, thousands of injuries, and widespread soil liquefaction that caused billions of dollars of damage to civil infrastructure.

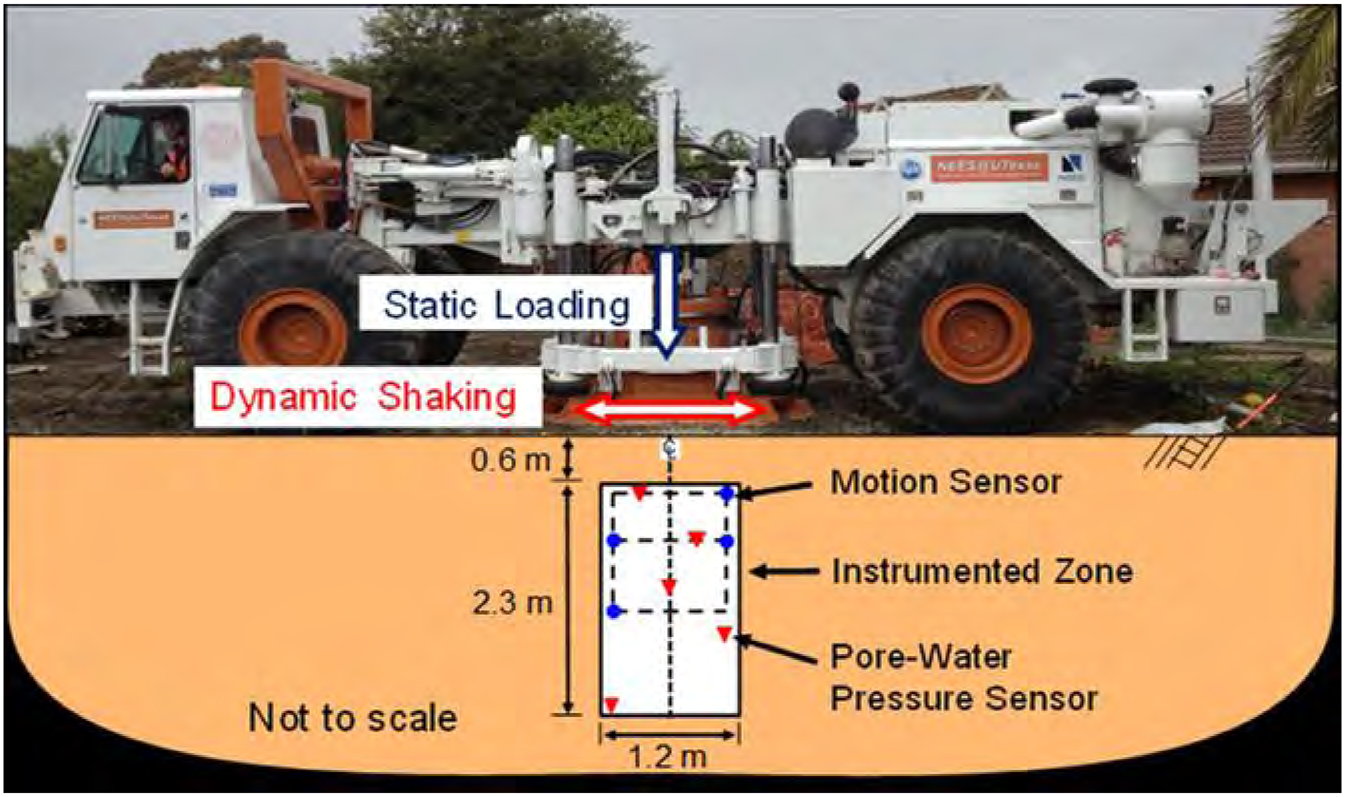
While it is hard to quantify all economic factors, most estimate the Christchurch earthquakes resulted in approximately $40 billion NZD in damage (roughly 20% of the entire New Zealand GDP). These statistics are shocking, considering that New Zealand seismic design standards are on par with countries such as the U.S. and Japan. Clearly, the "old Christchurch" was not resilient or sustainable, and in situ testing and research are needed to build a "new and resilient Christchurch."

The 2010-2011 Canterbury earthquakes caused repeated, widespread and severe liquefaction throughout the suburbs of Christchurch. There was a great need to investigate simple, cost-effective ground improvement methods for increasing the resilience of residential construction during future earthquakes.

Such ground improvement techniques could be used worldwide to reduce the impacts of liquefaction. As such, a series of full-scale field tests of various shallow ground improvement methods was initiated using T-Rex (one of the NHERI@UTexas mobile shakers). This effort was sanctioned by four New Zealand authorities [Earthquake Commission (EQC), Housing New Zealand (HNZ), Canterbury Earthquake Recovery Authority (CERA), and Ministry of Business Innovation and Employment (MBIE) and partially funded by NSF.

The four ground improvement methods selected by New Zealand authorities for the test trials were:

1. Rapid Impact Compaction (RIC), also known as dynamic compaction.
2. Rammed Aggregate Piers (RAP).
3. Low-Mobility Grouting, also known as compaction grouting.
4. Construction of one or two rows of horizontal beams beneath residential structures using in-situ soil mixing.



T-Rex shaking an instrumented natural-soil zone in Christchurch, NZ (Photo: Kenneth H. Stoke, University of Texas at Austin).

The relative effectiveness of these ground improvement methods to inhibit liquefaction triggering was evaluated by controlled shaking of the ground and monitoring the subsurface movements and dynamic pore-water pressures using embedded sensor arrays.

Specifically, in-situ determinations of shear strains and pore-water pressure ratios were made within each of the four ground improvement zones and within nearby unimproved (natural soil) zones at three separate test areas in the city.

Test results show that the RIC and RAP methods were found to be effective at mitigating liquefaction triggering. This research, aimed at rehabilitating a city devastated by earthquakes and increasing community resilience against future hazards, could not have been completed without the in-situ testing resources of NHERI@ UTexas.

Similarly, the NHERI@UTexas equipment can enable future research efforts investigating liquefaction performance of in situ natural and improved soils for enhanced seismic performance.

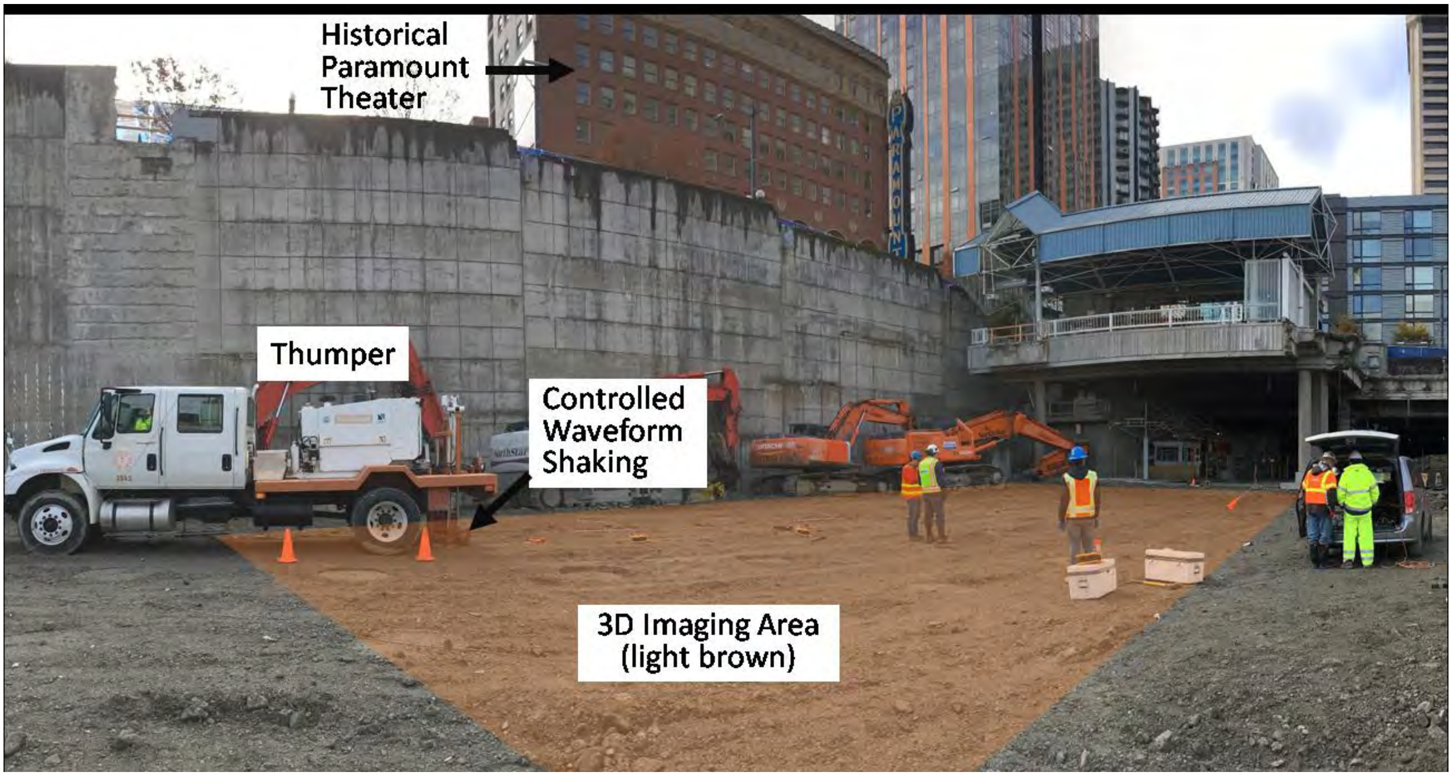
Performing Deeper, More Accurate, and Higher Resolution 2D/3D Subsurface Geotechnical Imaging

In earthquake engineering, the need to develop reliable, site-specific subsurface models with accompanying dynamic material properties cannot be overstated. Subsurface materials nearly always play a critical role in the areal extent and severity of damage associated with earthquakes.

However, these materials are the least investigated, most variable, and least controlled of all civil infrastructure materials. All forms of ground motion prediction, from rudimentary to complex, rely on some knowledge of the subsurface small-strain shear modulus (Gmax)/shear wave velocity (Vs) profile.

The more accurately this information is known, the more accurately we can estimate the amplitude and frequency content of future seismic ground motions. Without a good subsurface Gmax/ VS model, these attempts are futile.

The deep profiling with the NEES@UTexas equipment in Christchurch is an excellent example of the importance of this work.



Thumper acting as a controlled seismic source for 3-D imaging of soil stiffness (Photo: Kenneth H. Stokoe, University of Texas at Austin).

The ground motions recorded during the Christchurch Earthquake significantly exceeded design levels at many locations in the city. While higher-than-expected, short-period ground motions were not a surprise, given the closer-than-expected fault rupture, the higher-than-expected long-period ground motions could not be explained and were postulated as potentially the result of site effects (1D amplification), basin-edge effects (2D/3D amplification), and/or rupture directivity effects. Detailed back-analyses aimed at reproducing the recorded ground motions were hampered by the lack of information on the Vs structure of the deep inter-layered sand and gravel deposits of the Canterbury basin. Therefore, confidence in predicting more robust, future design ground motions from forward analyses was severely lacking.

The unique equipment resources of NEES@UTexas (now NHERI@UTexas) were mobilized to Christchurch with the goal of performing ultra-deep (> 400m), non-intrusive Vs profiling to aid in developing a 3D velocity model of the Canterbury basin. The combined surface wave testing program using a large, active source (T-Rex) and passive, ambient-wavefield monitoring had never been applied before. This unique equipment, coupled with advanced signal processing and data analysis techniques, allowed 500- to 1000-m deep Vs profiles to be developed at each site, with accompanying estimates of uncertainty. These ultra-deep Vs profiles revealed subsurface structure, including a very strong, deep impedance contrast, that played a significant role in the long-period amplification observed in the recorded ground motions.

This information could not have been economically obtained in any other way. However, there is still much future work to do in refining and validating these methods. Furthermore, as these combined large, active-source and ambient-wavefield techniques have been employed only sparingly in the U.S., much work remains to study the Vs structure beneath cities in high seismicity areas underlain by deep sedimentary deposits, such as Los Angeles, Seattle, Salt Lake City, Memphis, and Charleston.

Continuous 2D/3D In-Situ Profiling for Site Characterization and Anomaly Detection
A major scientific and engineering breakthrough would be the ability to rapidly and nonintrusively 2D/3D image the subsurface for the purpose of site characterization and anomaly detection in the top 30 m.

In this context, anomalies refer to any abnormality/irregularity such as cavities/voids, soft/weak zones, dipping layers, buried objects, etc. Consider for example the levee systems in the U.S., which consist of approximately 160,000 km of earth embankments constructed to protect cities, urban areas, and farmlands from flooding. The reliability of this levee system is largely unknown under the demands of natural hazards such as flooding/hurricane inundation and earthquakes, and the cost to repair or rehabilitate these levees is currently estimated to be $100 billion. The ability to rapidly and reliably profile levee systems in order to search for weak zones would greatly increase the resiliency of civil infrastructure, while simultaneously reducing the cost to do so. The NHERI@UTexas equipment can be used to help solve this type of 2D/3D imaging problem.

Another example of 3D imaging with NHERI@UTexas mobile shakers to characterize the subsurface and identify where soft/weak zones exist is shown in the figure above. In this example, Thumper, our smallest shaker, is being used as a controlled seismic source in an excavation in downtown Seattle, WA. The purpose of this stiffness imaging using body and surface waves is to predict the lateral movements of the walls surrounding the excavation. The movements of these walls have to be within limits that affect the performance of adjacent old and new structures, a highway, several roadways and a tunnel. The excavation is being dug as part of the construction of a new convention center in downtown Seattle, WA.

Developing Rapid, In-Situ Methods for Structural Health Monitoring and Soil-Foundation-Structure Interaction (SFSI) Studies
The mobile field testing equipment of NHERI@UTexas can also be used to help answer critical structural engineering research questions, under realistic conditions, that have not been addressed previously.

Several of the other NHERI structural engineering experimental facilities (e.g., Lehigh, UCSD) provide resources for quasi-static, pseudo-dynamic, or shake table testing of structural specimens that have idealized boundary conditions (e.g., fixed foundation and/or assumed stationary inflection points at actuator loading locations).
These types of tests are ideal for characterizing nonlinear performance of structural components under lateral loading; however, they often neglect the complex soil-foundation-structure interaction (SFSI) that can critically impact performance of complete civil infrastructure systems. Experimental facilities that address SFSI often involve small-scale structural models in containers of uniform soil excited on a shake table or in a centrifuge (e.g. the NHERI centrifuge facility at UC-Davis).

These small-scale specimens may not be representative of actual construction methods or structural materials and only consider a limited range of idealized soil conditions. While scaled and idealized laboratory experimental research programs provide important findings for understanding structural behavior, the next frontier of natural hazards research requires that researchers couple their findings from idealized laboratory testing with investigations of large-scale, complex structure-foundation-soil systems.

The mobile NHERI@UTexas equipment can provide capabilities for in-situ testing of realistic and complex soil-foundation-structure civil infrastructure systems in a range of soil conditions.

Collaborative and Shared-Use Opportunities
Dynamic characterization of civil infrastructure through in-situ testing can be used along with laboratory testing of specimens at NHERI facilities such as UC-Davis, UCSD, and Lehigh to validate and improve numerical models of soil-foundation-structure systems for computational studies using, for example, the NHERI SimCenter resources.

Also, following the NSF shared-used policy, researchers from around the United States as well as other countries can involve the NHERI@UTexas large-mobile shakers and associated personnel on their projects. One example of this collaboration is presented in the call-out box describing our efforts with researchers at Portland State University.

(Photo: Kenneth H. Stoke, University of Texas at Austin).

NHERI Large Mobile Shakers: Shared-Use Helping Build Resilient Cities

The NHERI@UTexas Large Mobile Shakers form the nation's largest dynamic mobile testing facility. "Have shakers, will travel" is our slogan.

Under the NHERI shared-use policy, researchers from Portland State University, Professors Arash Khosravifar and Diane Moug, have used the T-Rex and Rattler mobile shakers to evaluate a new bio-ground improvement method developed at the Center for Bio-mediated and Bio-inspired Geotechnics (CBBG) at Arizona State University.

The field testing capability available at NHERI@UTexas is especially important for testing difficult to sample materials like the Willamette silt in the Portland area.

Appendix B12: University of Washington RAPID Facility

FACILITY OVERVIEW

The RAPID Facility provides infrastructure and services that will allow the execution of the next-generation of disaster rapid response research and data-enabled science. By supporting the prompt collection of high-resolution integrated data sets, the RAPID Facility will play a central role in providing the academic, research, and professional communities with an unprecedented amount of high-quality, open-source, disaster engineering, geophysical, social, and behavioral data.

In addition, software tools created by the RAPID Facility and DesignSafe will allow for the archiving, integration, exploration, and visualization of complex data sets, which have been a key challenge for disaster rapid response research. Together with the rich data, these software tools will facilitate collaboration among experts across different fields to support advancements at the intersections of the natural hazards specialty disciplines.

Use of the RAPID facility drone-lidar system to image an active landslide in Oregon (Photo: RAPID Facility).

A particularly unique aspect of the RAPID Facility is its planned portfolio of geospatial, image-centric data collection equipment. High-resolution georeferenced laser, image, and video data collected from full fields of view (top to bottom; inside and outside) of civil infrastructure within affected regions will support development of 3-D post-event civil infrastructure models.

Such models can be safely interrogated to extensive detail when research teams return to their home institutions—a feature that will allow researchers the time and vision to collaboratively continue to discover new and important aspects of the impact of the surveyed event.

The main elements of the RAPID Facility are:

- A portfolio of state-of-the-art data collection tools, including terrestrial lidar, SfM and gigapixel imaging, airborne (UAS) lidar and imaging, seismological instruments, building survey and monitoring equipment, field-deployable sensors (including for real-time collection during an event), ground investigation equipment, and informational and communication technologies (ICTs) such as equipment to collect message streams (e.g., Twitter) and infrastructure to support crowd-sourced data.
- A collection of new software tools that include (i) an application to facilitate standardized data collection by field teams, (ii) software to integrate complex, multimode geospatial data sets, (iii) a custom Web portal to support social science reconnaissance, and (iv) a citizen science application to facilitate the public and businesses in contributing post-disaster observations and data.
- Education, outreach and training services to (i) train the natural hazards community on state-of-the art field data collection and analysis techniques and encourage user collaboration, (ii) involve citizen scientists in natural hazard science and engineering, (iii) engage members of the professional community who have not traditionally participated in disaster investigations, and (iv) facilitate information exchange by making reconnaissance data publicly available.
- Initial deployment services for the capture of highly perishable data by facility staff, select members of the RAPID Facility team, and possible other experts from outside the facility. Advisory services provided by the

RAPID facility users and staff deployed to the South Island of New Zealand in support of an NSF project to laser scan and characterize precarious rock slopes, which threaten hikers and tourists at the Fox Glacier National Park (Photo: Joseph Wartman, Natural Hazards Reconnaissance Facility, University of Washington).

RAPID Facility equipment and discipline specialists to assist reconnaissance teams with the planning of safe and successful field missions. Such services will also help facility users identify unique data gathering opportunities in support of the broader Five -Year Science Plan for NHERI.

- The Rapid Facility personnel will form deployment teams with multi-hazard expertise that will perform natural hazard reconnaissance and collect perishable data. The project leadership team has expertise in the strategic areas of interest (e.g., geotechnical, structural, lifelines, social science, wind storm, storm surge, storm waves, seismic, tsunami, and advanced data collection technologies) for reconnaissance and a wealth of reconnaissance experience.
- A RAPID Facility center housed at the University of Washington. This center will include a 3-D mini-CAVE (computer-assisted virtual environment) for users to view and preliminarily analyze the various forms of image data collected during field campaigns. The use of such technology has vastly improved data interpretation for members of the reconnaissance team after recent disasters. The center will also include a work facility for calibrating and maintaining field equipment.

Additional information regarding the facility and leadership group is available at the DesignSafe website: rapid designsafe-ci.org/.

RESEARCH OPPORTUNITIES

Community Resilience Framework
To better understand the direct and indirect impacts of natural hazards events, a framework is needed to measure, monitor, and evaluate community-level resilience. The lack of historical data on community impacts and recovery following past disasters presents a major impediment to meeting this goal. The RAPID Facility will help to address this challenge by providing tools to systematically collect and archive post-disaster data pertinent to engineering and the natural and social sciences.

Equally important will be the RAPID Facility's data integration software, which will aid in linking data and identifying connections across different systems (e.g., civil infrastructure and social/economic processes).

This knowledge can be used to evaluate the utility and validity of the wide range of community resilience frameworks—a significant gap in the state-of-the-art in disaster science and engineering.

Hazard and Impact Simulation and Decision-Making
Computational simulation and forecasting of the timing and regional distribution of the hazard itself, as well as its physical and social impacts, are critically important for decision-making, planning, and mitigation.

Yet, such simulations—which span a range of temporal scales, including both short-term (e.g., informing electricity restoration with expected damage patterns) and long-term timeframes (e.g., identifying local vulnerabilities for risk reduction policy making), including impacts from consecutive events and/or concurrent hazards (e.g., multiple storms in one season)—present a crucial challenge to the professional community.

New, high-performance computing platforms provide the opportunity to make significant progress with this challenge. But such simulations are highly complex and require extensive hypervariate data sets for model development and testing.

Since many of these models are inherently information driven, they also require high quality data (e.g., initial and boundary conditions) to provide reliable forecasts. Nearly all of the RAPID Facility's elements (tools, software, training, to include airborne data acquisition and citizen science) will serve to address the data needs of simulations models across a wide range of geospatial scales.

Hazard Mitigation
Renewal and retrofit (e.g., floodproofing) strategies are essential to mitigate hazards posed to civil infrastructure. The development of effective mitigation strategies requires computational models (see above), design methods, and construction standards that, when harmonized, are capable of identifying critical vulnerabilities and quantifying the impacts of risk reduction measures.

In addition, post-event data are needed to evaluate loss estimation methodologies, such as HAZUS-MH, investigate the efficacy of mitigation approaches, and provide feedback for state-mandated insurance incentives for homeowners who employ mitigation. The RAPID Facility's multi-scale tools will provide the means to address these needs. For example, terrestrial lidar and building survey equipment could be used to collect data on the seismic performance of retrofitted buildings. Lidar can be used in coastal communities after hurricanes to quantify morphological changes, civil infrastructure damage, and ecological damage in detail and on a large scale. Importantly, all of these data sources can be harmonized and overlaid with imagery to develop 3-D models of disaster-impacted regions or damage-affected civil infrastructure.

Design Tools
Improved ability to characterize uncertainty in the predictive capability of design tools is essential to better exploit, for example, newer, more sustainable and resilient building materials and foundations, and novel hard and nature-based engineering measures (e.g., dunes, wetlands, and grey infrastructure) to reduce the hazard(s). Improved design tools are also needed to capitalize on innovative structural, geotechnical, and lifeline concepts.

Performance-based design provides the framework for addressing this challenge, but such design relies on high quality performance data to define model relationships (e.g., fragility functions). This RAPID Facility will provide the tools to help meet this challenge.

For example, sensors could be installed on structures and earth systems to monitor response to aftershocks, and aerial imagery could be used to validate the performance of wind resistant roof covers.

The following presents examples of the types of projects the RAPID Facility can support, all of which cut across two or more of the RAPID Facility's four supported Critical Areas.

Research Example 1

Characterize vulnerability of infrastructure to natural hazards damage. The RAPID Facility supports development of high-resolution, geocoded data sets to constrain or otherwise reduce uncertainties in stochastic-based models of the vulnerability of infrastructure to natural hazards damage. These include aerial photography, lidar and ground-based documentation of post-event damage. Current models are populated with assumptions regarding probabilistic structural component capacities, load paths, the influence of aging, and cascading damage from neighboring structures. Model projections of scenario-based economic impacts and cost-benefit assessments of mitigation strategies will benefit from refinements to these assumptions, informed by detailed geocoded field data stratified by building code and localized hazard intensity.

Research Example 2

Characterize structural response to ground shaking. Simulation of structural response to ground shaking is largely validated through comparison with data from experiments in controlled laboratory environments and with data collected from reconnaissance following earthquakes, such as the data collection supported by this RAPID Facility. The structural models may be focused on component behaviors, building behaviors, or even the behavior of entire classes of buildings through the development of fragility functions. Such observation-based fragility data is also critical to loss estimation software such as FEMA HAZUS-MH.

Research Example 3

Characterize inundation, waves (including propagation onshore), erosion (e.g., of shorelines, islands, and dunes), and other destructive physical phenomena associated with natural coastal hazards. The RAPID Facility supports provision of the rare, but critical, perishable data needed to quantify underlying physical phenomena and to develop, validate, improve, and reduce uncertainty in physics-based, computational modeling of wind, waves, storm surge, tsunami inundation, sediment transport, morphological change, and other related processes representing the inter-related, destructive forcing mechanisms.

Data during and following natural coastal hazards are needed to characterize, for example, inundation extent, flow speeds, flow depth, wave conditions, wind speeds, soil properties, erosion and accretion, and inundation-related damage to civil infrastructure and the natural environment.

These data will help improve understanding of, for example, (a) the interplay between the natural landscape (land cover, topographic features), the built environment (critical infrastructure, homes), and hydrodynamics, (b) how and when concurrent multi- hazard components (e.g., flooding by wave runup vs. wind surge vs. other phenomena [rainfall runoff near the coast]; wind vs. flooding) lead to the functional failure of critical infrastructure—ultimately leading to more resilient communities.

Research Example 4

Characterize and quantify socio-technical loss due to and recovery from natural hazards. Lifelines and other elements of the built environments are ultimately socio-technical systems. That is, there are core social, economic, and behavioral components to the development, operation, and maintenance of all physical systems.

There is a crucial need for post-disaster research, such as that which can be supported by this RAPID Facility, to better unpack and quantify the socio-technical dimensions related to damage, restoration, and reconstruction of elements of the built environment. This research is needed to advance existing socio-technical loss and recovery models, as well as to develop new ones. Most socio-technical modeling efforts to date have focused on modeling disaster losses.

Research Example 5

Characterize co-seismic landslide displacement. The RAPID Facility supports provision of appropriate data to test, verify, and calibrate co-seismic landslide displacement models. Specifically, the RAPID Facility's portfolio of geomatics technologies such as lidar could be used to capture complex ground deformation patterns and landslide morphological features, which erode quickly after an event.

There are relatively few high quality case histories of co-seismic landslide displacement, which represents an important research need in the field of geotechnical earthquake engineering.

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