2020 Vision

for Earthquake Engineering Research

Report on an OpenSpace Technology Workshop
on the Future of Earthquake Engineering

A Report on the NSF-Funded Workshop

Vision 2020: An Open Space Technology Workshop on the Future of Earthquake Engineering

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St. Louis, Missouri, USA

by

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EXECUTIVE SUMMARY

Earthquake engineering has matured over the past decades. This process has been reactive, driven, to a large extent, by needs to mitigate damage that occurred in recent earthquakes. Today, a decade after the last significant U.S. earthquake, in an economic recession, with the public focus on climate change and energy issues, earthquake engineering faces a challenge to re-new itself.

This report provides a brief summary of the discussions that took place during the January 25-26, 2010 workshop, *Vision 2020: An Open Space Technology (OST) Workshop on the Future of Earthquake Engineering*. Vision 2020 was established to formulate a vision of where earthquake engineering in the U.S. needs to be in 2020 to vigorously address the grand challenge of mitigating earthquake and tsunami risk going forward.

The participants of the workshop unanimously identified resilient and sustainable communities as the over-arching long-term goal to achieve in earthquake engineering. The participants also identified seven principal directions in earthquake engineering research where significant progress needs to be made by 2020 to attain the resilient and sustainable community goal. These research directions are: 1) metrics to quantify resilience; 2) tools for hazard awareness and risk communication; 3) reducing the risk posed by existing structures and infrastructure; 4) developing and implementing new materials, elements and systems; 5) monitoring and assessing resilience; 6) means to simulate resilience of systems; and 7) implementation and technology transfer. The definition of each of the research directions, their intellectual merit and anticipated broader impact, the crucial role of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES), as well as the enabling technologies and fundamental capabilities needed to make substantial and rapid research progress, are discussed within this report.

While the goal of resilient and sustainable communities is evolutionary, achieving it requires a revolutionary change in the earthquake engineering processes deployed to generate fundamental knowledge and develop enabling technologies. Working towards this goal will transform the discipline of earthquake engineering into a complex system of interacting disciplines where new knowledge is generated through intellectual efforts at the intersections of the constituent branches of engineering, fundamental sciences and social sciences. Such transformation of earthquake engineering will broadly impact the coming generations of students through new multi-disciplinary education, research and practice.

Acknowledgement

This workshop was supported by the NSF CMMI Directorate through grants #1004951 and #0957567 (Dr. Joy Pauschke, Program Director). The workshop was also held in partnership with NEEScomm, the managing organization for the NEES network. The workshop organizers gratefully acknowledge the significant contributions of Mr. Wei Song, a doctoral candidate at Purdue University. We also appreciate the detailed review by several members of the earthquake engineering community, including Ian Buckle, Timothy Hower and Michael Sherraden.

The findings, statements and opinions presented in this report are those of the authors and workshop participants, and do not necessarily represent those of the National Science Foundation.

Preface

This report provides a brief summary of the discussions that took place during the January 25-26, 2010 workshop, *Vision 2020: An Open Space Technology (OST) Workshop on the Future of Earthquake Engineering*. Vision 2020 was established to formulate a vision of where earthquake engineering in the US needs to be in 2020 to vigorously address the grand challenge of mitigating earthquake and tsunami risk going forward. Drs. Shirley Dyke and Bozidar Stojadinovic organized the workshop. The organizers, whose primary research area is structural earthquake engineering, formed the Workshop Planning Committee (WPC) comprising the representatives from other areas of Earthquake Engineering in October 2009. Members of the WPC were: Dr. Nicolas Luco (ground motions, USGS); Dr. Pedro Arduino (geotechnical, University of Washington, Seattle); Dr. Maria Garlock (structures and materials, Princeton University); Dr. Solomon Yim (tsunami, Oregon State University); and Dr. Julio Ramirez (NEEScomm). The WPC met by teleconference and exchanged data by e-mail during the workshop preparation phase.

The goal of the WPC was to facilitate invitation of a balanced group of participants, representing the constituent earthquake engineering specialties, spanning research, government and industrial participants, as well as spanning the generational, gender, racial and ethnic diversity of the earthquake engineering community. The 78 attendees are listed in the Appendix.

The objectives of the 2020 Vision workshop were: 1) to chart the principal new directions in earthquake engineering research, practice, education and outreach for the earthquake engineering community over the next 10 years, and to postulate the needs beyond 2020; and 2) to reflect on the role of the current NSF NEES facilities in meeting the research needs of the earthquake community and to elucidate what new facilities would facilitate rapid progress along these new directions. The workshop participants generated a set of 40 diverse topics during the first day (see Appendix). These topics were discussed in terms of their potential for having an impact on how our society responds to earthquakes and other hazards. During the second day of the workshop, these topics were refined to formulate the overarching goal and the principal research directions that should be undertaken to advance the earthquake engineering community by 2020.

Open Space Technology (OST) was used to conduct this workshop. OST is a method to run meetings of groups of any size to address complex, important issues and achieve meaningful results quickly (www.openspaceworld.org/). OST is a self-organizing process: participants construct the agenda and schedule during the meeting itself. OST is also a method to allow a diverse group of people to jointly address complex and possibly controversial topics. Most importantly, it provides the space for everyone in this group to express his or her opinion and a way for that opinion to be heard and affect the final outcome. The workshop was facilitated by a professional facilitator, Mr. Pat Sanaghan.

This report is a result of the collaborative efforts of the workshop organizers and WPC members. The organizers and WPC members played key roles in facilitating the final discussions on the seven research directions identified by the workshop participants. The first drafts of research direction outcomes were written immediately after the workshop. These drafts were subsequently refined in a series of teleconference meetings and finalized in October 2010.

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Introduction

Earthquake engineering has matured over the past decades. This process has taken this engineering discipline from its structural engineering roots in the first lateral load code provisions made in the 1930's through an integration of earth sciences, structural and geotechnical engineering, structural mechanics, architecture, numerical and probabilistic mathematics, education and social sciences into what we today know as earthquake engineering. The focus on performance measured by the consequences of an earthquake on the function of a stricken structure and/or a stricken community is a direct result of the work of the three NSF-supported earthquake engineering research centers during the past decade. Today, the practicing community is moving towards a performance-centric approach to design through efforts like the ATC-58 Project and the development of risk-targeted ground motion maps in ASCE 7-10 (ATC, 2006; ASCE 2003b).

The George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) is a major national resource that plays an essential role in the nation's strategy for reducing losses from future earthquakes (NRC, 2004; NIST, 2008). This NSF-supported network of structural, geotechnical, tsunami and field fixed and mobile laboratories provide the means to conduct complex experimental and numerical simulations of seismic response of structures and infrastructure with capabilities not available previously. The NEES network aims to provide a fertile environment for collaboration of teams capable of tackling major earthquake engineering challenges in a multidisciplinary fashion. Thus, the capabilities and continued operation of the NEES network to best address the needs of the earthquake community should be considered in parallel with any discussion of the vision for the future of the earthquake engineering disciplines.

The fortunate absence of a major damaging earthquake in the U.S. since the 2001 Nisqually earthquake has had three major effects: a dilution of focus among the research community; a divergence of priorities between the practice and research communities; and, earthquake mitigation is not keeping pace with technologies from other fields that could make radical advances toward developing resilient communities. The research talent is drawn away from earthquake engineering towards major initiatives on energy efficiency and green technologies, while the focus of the majority of the practicing community remains delivering earthquake safety at minimum cost to developers. This leads to difficulties in determining the direction of the next major earthquake engineering initiatives and in focusing the projects using the NEES network. In turn, development of the next generation of earthquake engineering researchers and practitioners is becoming constrained. Together with limited funding, the lack of a focused, community-driven vision will hinder future advances in earthquake engineering in the US.

The next 10 years are crucial for evolution of this engineering discipline. The lack of focus is also a unique opportunity to set the stage for development of areas of earthquake engineering that would not have emerged when driven by an earthquake emergency. Three principal directions are available: 1) development of new structural and infrastructure systems, which require significant time to develop and validate; 2) solutions for major community-level or industry-level earthquake-related problems, which require a multi-disciplinary approach and teams drawn from diverse but complementary backgrounds that need time to come together; and 3) introduction of global and "external" research trends, such as energy efficiency and green building technology into earthquake engineering as well as integration of earthquake engineering with major research initiatives and developments in information technology, new materials and machines, and cyber-physical systems.

Several recent reports support the need for a strong U.S. presence in earthquake engineering research. Most recently, a series of NSF workshops has focused on the major research directions moving forward in several key areas within earthquake engineering (Wight, 2010; NIST GCR 09-917-2). Furthermore, ASCE's latest infrastructure report card (ASCE, 2009) indicates that the current condition of all elements of the nation's civil infrastructure is barely passing, making it much more vulnerable to earthquakes and other hazards. In 2003 EERI proposed a comprehensive research and outreach plan focused on improving our ability to manage risk and to transfer these findings into practice (EERI, 2003). In 2004, the National Research Council went a step further by proposing a grand challenge to the earthquake engineering community including recommendations on the role of NEES and NSF as well as achievements that would be made possible by the deployment of new information and communication technologies (NRC, 2004). Furthermore, the National Academy of Engineers has identified *Restore and Improve Urban Infrastructure* as one of the 14 Grand Challenges in Engineering (http://www.engineeringchallenges.org/). EERI (2008) has also delineated the role earthquake engineering has in enhancing public safety and discussed the potential contributions of earthquake engineering to the mitigation of other hazards beyond earthquakes.

The National Earthquake Hazards Reduction Program (NEHRP) strategic plan (http://www.nehrp.gov/pdf/strategic_plan_2008.pdf) discusses the need for developing and applying knowledge generated from multidisciplinary research in earthquake resilience and includes support for operating key research and data collection facilities (i.e., ANSS, NEES). The plan links NEES to a number of strategic priorities, including advancing understanding of earthquake processes and impacts; further developing performance-based seismic design; improving techniques for evaluating and rehabilitating existing buildings; improving understanding of the social, behavioral, and economic factors related to implementing mitigation strategies; developing advanced risk mitigation technologies and practice; and developing resilient lifeline components and systems.

The 2020 Vision workshop was organized with the goal to formulate a vision of where earthquake engineering research in the U.S. needs to be in 2020 going forward through direct engagement of a large portion of the earthquake engineering community. The objectives of the workshop were: 1) to chart the principal new directions in earthquake engineering research, practice, education and outreach to be adopted by the earthquake engineering community in the next 10 years, and to postulate the principal goals for earthquake engineering beyond 2020; and 2) to reflect on the role of the current NSF

NEES facilities in meeting the research needs of the earthquake community and to elucidate what new facilities would facilitate rapid progress along these new directions.

The outcomes of this workshop are presented in this report. The participants of the workshop unanimously identified resilient and sustainable communities as the overarching long-term goal to achieve in earthquake engineering. While the overarching theme was consistent with the goal of the new National Earthquake Hazards Reduction Program (NEHRP) plan for achieving resilient and sustainable communities, the participants recognized that work on achieving this goal could take the research community beyond 2020. The participants proceeded to identify seven principal directions in earthquake engineering research where significant progress needs to be made by 2020 to attain the resilient and sustainable community goal. These research directions are: 1) metrics to quantify resilience; 2) means for hazard awareness and risk communication; 3) challenge posed by existing structures and infrastructure; 4) opportunities to use new materials, elements and systems; 5) methods for monitoring and assessment of resilience; 6) means to simulate resilience of systems; and 7) methods for implementation and technology transfer. A description of each research direction is provided herein, along with the intellectual merit and broader impacts. Furthermore, the workshop participants considered the enabling technologies and fundamental capabilities needed to make substantial and rapid research progress.

Workshop participants also reflected on the role that the NEES network is playing in making progress toward achieving the vision of resilient and sustainable communities. To date, NEES has gained worldwide recognition in advancing our ability to conduct earthquake engineering simulation. NEES will also play a crucial role in meeting the unprecedented need to rehabilitate the vast stock of existing U.S. civil infrastructure. Furthermore, NEES is well positioned to provide the proof of concept testing necessary for emerging technology and substantiating evidence for its implementation. In addition, the NEES network will impact a broad cross section of society by generating opportunities for training the next generation of researchers, creating linkages to practitioners and policy makers to facilitate adoption and implementation of new technologies, providing educational materials and a strong public outreach component.

Working towards the *2020 Vision* of resilient and sustainable communities will revolutionize the discipline of earthquake engineering. The development of resilient and sustainable communities requires understanding and simulation of both the physical systems and the human systems within the communities. Thus, crossing the traditional boundaries between engineering and social science will generate necessary fundamental knowledge and enabling technologies. Such a transformation of earthquake engineering will serve to improve the disaster resilience of communities, and demonstrate that investments in earthquake safety can reduce losses from other hazards and improve lifecycle performance, while also developing the nation’s human resource base in the earthquake safety field.

Resilience: An Overarching Theme

The term "resilient" is defined as (1) capable of resisting a shock without permanent deformation or rupture (2) tending to recover from or adjust easily to misfortune or change" (http://www.merriam-webster.com/netdict/resilience). Resilience is distinct from vulnerability. With regard to our communities, the definition of resilience is related to their ability to return to normalcy quickly after the occurrence of a significant event such as an earthquake, tsunami, flood, hurricane, etc.

The development of resilient and sustainable communities involves the consideration of both the physical systems (e.g. healthcare, buildings, highways, sanitation, subways, communications, energy facilities) and the human systems (e.g. the local population and its associations such as schools, banking and insurance systems; the socioeconomic and legal frameworks that guide decisions) within the communities. With this in mind, although there may be damage to our structures and appropriate planning may have taken place in anticipation of potential outcomes, one important characteristic of resilience is that redundancies have been put in place to fill gaps that may arise to ensure that a regular daily routine is possible for the affected population.

Earthquake engineers can most appropriately address the goal of resilience in our communities. Earthquake engineering is by its nature a multidisciplinary field, linking earth scientists, engineers and social scientists in the analysis of the effects of earthquakes. However, earthquake engineers also need to make a move toward lifecycle engineering to develop resilience in our communities. Thus, we must change from focusing only on the cost of our built environment, to pursuing opportunities to understand and make decisions based on the entire life cycle of our systems. Furthermore, humans must interact each day with the built environment, and yet those who study the built environment have little understanding of the motivations and response of the human systems within our communities. Improving the ability of our communities to bounce back after major events will require integration of human systems research, and will result in great progress in our ability to save lives, reduce economic disruptions, and enhance day-to-day life.

"**Our goal is to ensure a more resilient Nation** - one in which individuals, communities, and our economy can adapt to changing conditions as well as withstand and rapidly recover from disruption due to emergencies."

-- President Barack Obama
National Preparedness Month,
A Proclamation by the President
of the United States of America,
September 4, 2009

Seven research directions needed to develop resilient communities were identified by the 2020 Vision Workshop. These are: metrics to quantify resilience; the means for hazard prediction and risk assessment; continued challenge posed by existing structures and infrastructure and the orderly renewal of the same; opportunities to use new materials, components and systems; methods and tools to develop inventories of sufficient fidelity for monitoring and assessment for resilience; means to simulate resilience of systems at regional scale; and methods for implementation and technology transfer. These goals and the actions needed for building resilient communities are discussed in the subsequent sections.

Metrics to Quantify Resilience

Our futuristic vision for resilient communities is one that has transparent expectations of community performance before, during and after an earthquake. In other words, a community should be able to identify how to prepare for an earthquake, how it will respond during an earthquake, and how it will function and recover after an earthquake. Such expectations of community performance should be defined in terms of both functionality and time after an event. They also need to be communicated in simple, concise terminology to the public. To this end, earthquake engineers need to be able to interpret the expected community performance descriptions in terms of engineering performance objectives (within the context of resiliency) and be able to measure resiliency to evaluate the expected performance.

Each community should define an overarching goal (e.g., number of days to recovery) and that goal should be more than just safety.

However, our goal is a resilient community, not just a resilient building. While a building is a part of the community, our vision and goals are broader than that. The community comprises the human and social components of a given region as well as groups of buildings connected by function and correlated by engineering characteristics. Thus, a building may be structurally safe, but not functional if its lifelines (water, electric, sewer, etc.) are not functioning. Furthermore, resiliency applies to the entire lifetime of a structure, not just a single event like an earthquake. Therefore designs for resilient performance must be considered for multiple hazards such as earthquake, fire following earthquake, hurricane, impact, blast, or whatever hazard may affect the given structure.

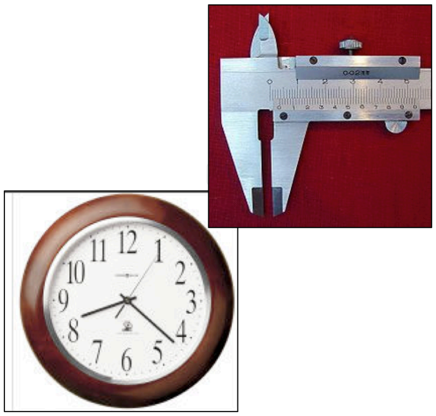


Figure 1: A community's performance must be measured in terms of both functionality and time.

Metrics for resilience can be categorized in the following three ways:

Performance goals: The performance goals are based on a qualitative definition (e.g., robust, redundant, rapid, etc., based on Bruneau and Reinhorn (2006) and Bruneau et al. (2003)). Once the qualitative definition is given, performance objective levels can be identified based on level of damage and length of time to recovery. As an example, the

San Francisco Planning and Urban Research Association's (SPUR, http://www.spur.org/) proposes performance objective levels for buildings and lifelines in a resilient community as described in the table below:

Table 1: Example - SPUR defined categories of expected performance

Category		Performance objectives
buildings	A	safe and operational
	B	safe and useable during repair
	C	safe and useable after repair
	D	safe and not repairable
	E	unsafe
lifelines	I	resume 100% of service levels within 4 hours
	II	resume 90% of service levels within 72 hours, 95% within 30 days, 100% within 4 months
	III	resume 90% of service levels within 72 hours, 95% within 30 days, 100% within 3 years

An evaluation of previously proposed performance objectives is needed, followed by some agreement as to what are more appropriate levels of performance objectives.

Response parameters: To understand if the performance objectives were met, we need to evaluate the response of the infrastructure to the event (e.g. earthquake); and to evaluate the response, we need to know what to measure. For example, within the context of structural performance we may want to measure drift and inelastic material response among other things. But we also need to evaluate the system performance (e.g., lifelines) and the interdependence of systems (e.g., the interaction of structure and nonstructural elements such as electric and water lines within the building). These measurements need to be made at the micro-level (e.g., connection details) and the macro level (i.e., community level). We cannot arrive at a community-level measurement of resilience without considering all the micro-level elements.

Quantitative measures: Whereas the qualitative measure uses words, the quantitative measure uses numbers. There is a need to quantify the micro- and macro-level resiliency. Then, these values must be related back to the performance objectives so that we can identify the category.

In developing these measures, we need to consider not only the interdependencies among the different infrastructure systems, but also between these systems and the community. Each community should define an overarching goal (e.g., number of days to recovery) and that goal should be more than just safety. The community should also prioritize the required functionality following a large event. For example, safety should be the first priority to minimize casualties. Following that, the goal should be functioning shelter, which means that the building is safe to occupy and the water, sewer, and electric are working. Finally, the community should resume normal work functions, which means being able to use transportation to arrive at their place of work, communication lines are functioning, as is the economy.

Intellectual Merit

The intellectual merit of developing metrics for resilience lies in determining how to make the measurements and bring them back to tangible outcomes. The focus of our efforts should be in identifying the qualitative performance goals, the methods to evaluate progress and the quantitative measurements to evaluate performance.

Broader Impacts

Each stakeholder in a community has a different vested interest in resilience metrics, which we broadly categorize into three areas: a reduction of direct cost, a reduction of casualties, and a reduction of business interruptions. Direct cost relates to the initial design, which may consider a higher price for resilient construction, plus the cost of repairs. Business interruptions cause indirect loss of income (e.g., loss of rent) and are also inconvenient for the tenant (e.g., must find temporary housing). The stakeholders and their main interest are summarized in Table 2.

Future NEES experiments should be designed to consider the impact on the community (e.g., cost, casualties, and business interruptions).

Table 2: Stakeholders and their Main Interests.

Stakeholder / Main Interests	**Reduction of Direct Cost**	**Reduction of Casualties**	**Reduction of Business Interruption**
Owner	X		
Regulator		X	
Tenants		X	X
Insurers and lenders	X		X
Communities, Policy makers	X	X	X

While currently there is no way to model loss of life robustly, engineers attempt to prevent substantial loss of life through robust design. Measurements of cost and business interruptions are currently heavily based on intuition. A more 'scientific' measure of these factors is needed. For example, we can use fragility curves to understand these losses.

Tools Needed and Role of NEES Facilities

The enabling technology needed to develop measures of resilience is high performance computing and computer tools suitable for such computing platforms. Advances in computing technologies will permit fast and advanced analyses so that the measurements can be made within a risk and reliability framework (which considers the uncertainties in the parameters). The measurements should be validated with NEES data that can be used to develop fragility curves, which in turn can be used to measure resilience quantitatively using loss estimation tools.

Future NEES experiments should be designed to consider the impact on the community (e.g., cost, casualties, and business interruptions). This means representing the broader response in an experiment, perhaps through hybrid simulation. For example, if studying a beam-to-column connection, the NEES simulation should indicate how that performance would affect the community based on the overall building response, which should not be limited to the structural integrity. Also, it is necessary to measure and evaluate the interdependence of systems (e.g., the interaction of structure and nonstructural elements such as electric and water lines within the building). Further, experimental data should be reported within the context of resilient metrics at the community level.

The metrics, or performance objective level, can be used as a tool for a rating system that is transparent to the community. Transparency would mean that the structural performance expectation is defined in simple terms and accessible to everyone. The rating can be listed in a catalogue online and/or posted on a plaque on the structure. Ideally the public will be engaged in this process. These concepts are already being pursued but the barriers are technical, administrative, and communication. Our 2020 Vision is that these barriers will be removed.

Hazard Awareness and Risk Communication

Our vision for 2020 and beyond includes the development of enabling technologies and tools to enhance the situational awareness of first responders (e.g., police, fire fighters, civil authorities, FEMA personnel) through real-time risk assessment. The tools will include new technologies to: assess the real-time structural integrity and predict the immediate post-hazard event environmental risks; communicate optimal rescue and mitigation actions; and assess the subsequent results. A fundamental requirement for these tools will be the development and implementation of smart sensors in structures and the environment, and real-time data collection and assimilation during and after the hazard events. These tools will span multiple time-scales during, immediately after, and long after the occurrence of the event.

The types of hazards usually encountered in a seismic event include the main earthquake, and other hazards induced by the earthquake including aftershocks, tsunamis, landslides, liquefaction, floods, and fires. The focus here will be on earthquakes and tsunamis since aftershocks are (subsequent) earthquakes, and landslides, floods and fires are consequences of some form of system failures (e.g., soil foundation, dams, levees, lifelines).

Our vision for 2020 and beyond includes the development of enabling technologies and tools to enhance the situational awareness of first responders through real-time risk assessment.

The early warning, assessment, and communication tools and the enabling technologies affect each other symbiotically as the need for the tools drives the development of enabling technologies and the developed technologies improve the effectiveness of the tools. The availability of advanced models for the various systems involved is crucial to the development of this capability. Early warning of earthquake hazard involves initial fault rupture forecasting and subsequent fault rupture evolution and ground motion simulation. Prediction of tsunami after an earthquake event using an analytical model involves obtaining measurements related to the earthquake such as focal depth, strike angle, dip angle, rake angle, slip length and width of the fault area. Such predictions will take a few minutes and, for distant tsunamis, can be improved continuously using real time data assimilation from NOAA tsunami measurements. Real-time nonlinear structural analysis tools could be assimilated with measured data, both of ground motion and tsunami loading and of structural response. These goals require development of not only new analytical models, but also new sensor technologies and data collection and processing systems.

Prediction of structural damage, injury and loss of life is a continuous process and involves multiple time scales. Once an earthquake occurs, seismologists may be able to provide several minutes warning of imminent strong aftershocks. The earthquake event itself is on the order of seconds to a few minutes. Aftershocks following a main earthquake event have the same order of duration (seconds to minutes). The occurrence of a tsunami depends on the fault information discussed above, and the tsunami event, which includes (a possible) drawdown, runup and subsequent rundown, is usually on the order of minutes. Time intervals between the main earthquake and aftershocks can be on the order of minutes, hours, days, and sometimes months. The time interval between an earthquake and subsequent tsunami depends on location of the earthquake and the affected area under consideration. For a "near field" or local tsunami, the earthquake focal point is near the tsunami inundation area considered, and the structure can be damaged by both the earthquake itself and the subsequent tsunami fluid impact loads. The time interval between the earthquake and tsunami inundation can be minutes to hours (for example a Cascadia subduction zone earthquake and coastal cities along California, Oregon and Washington). For a "far field" or distant tsunami, the earthquake focal point is far away from the tsunami inundation location and the time interval between the earthquake and tsunami inundation can be hours to days apart. Such is the case for tsunami inundation of coastal cities in Hawaii, Washington, Oregon and California induced by an earthquake on other parts of the Pacific rim, e.g. in Japan, Chile or Alaska.

Figure 2. Data being collected from sensor networks (e.g. NSF-supported Ocean Observatories Network) and strong motion systems (e.g., NEHRP Advanced National Seismic System) will inform our models for prediction and communication of risk.

Post-event risk assessment includes evaluation of the integrity of damaged structures to determine rescue operations. Such assessment requires real-time analysis and assimilation of measured data, which could include hybrid analysis. The advanced prediction and assessment tools will be advertized to the general public to enhance hazard and risk awareness, preparedness and post-event behavior.

We should take advantage of existing knowledge gained and documented in parallel hazards such as hurricanes and tsunamis (see “Communicating Hurricane Risk” and “TsunamiReady” by NOAA http://www.tsunamiready.noaa.gov/).

Intellectual Merit

The capabilities described above require the development of advanced nonlinear structural analysis tools that assimilate measured data in real-time, and the establishment of new sensor technologies and data collection and processing systems. The sensors, which are often inaccessible after installation, would best be self-powered, deriving their energy from the ambient environment. Achieving this vision also requires the adaptation of decision support tools for application to structural damage assessment and mitigation strategies.

> *The tools will enable engineers to provide short-term instantaneous predictions with continuously updated forecast based on real-time data monitoring and assimilation, as well as long-term post-earthquake risk predictions based on response simulation.*

Broader Impacts

First responders will have advanced decision support tools to enhance recovery operations and improve human safety. The public will be educated on awareness, preparedness and response to the hazards and associated risks.

Communication involves multiple stakeholders including engineers, police, fire department, search and rescue workers, local, state and federal officials, and the general public. The methods and tools of communication are determined by the messages to be conveyed, the targeted audience, and the desired outcomes.

Tools Needed and Role of NEES Facilities

Hazard prediction tools will be based on forecast information before the occurrence of an actual earthquake or a tsunami. The tools will enable engineers to provide short-term instantaneous predictions with continuously updated forecast based on real-time data monitoring and assimilation, as well as long-term post-earthquake risk predictions based on response simulation. These predictions will be used for post-hazard event search and rescue and accommodation of people affected by the hazard events.

The enabling technologies will need to be verified and validated through the existing NEES facilities. The real-time structural assessment and data assimilation tools will need to be tested in the large-scale structural and centrifuge facilities and shake tables. The tsunami research facility will be needed to test the tools for damage such as scour, liquefaction, and structural damage due to tsunami loads and fluid-structure interaction. The field testing equipment will enable verification and validation of the tools in full scale.

Renewal of Existing Structures

Existing vulnerable buildings and infrastructure assets are the number one seismic safety problem in the world today. In the U.S. alone, the 2006 National Research Council Report (2006) notes that 42 states have some degree of earthquake risk, with over 75 million Americans living in urban areas with moderate to high earthquake risk. In addition to unquantifiable potential impact from casualties and injuries, the Earthquake Engineering Research Institute (EERI) concluded in a 2003 report that the direct cost of losses in the built environment and the indirect economic cost (business losses) of a major earthquake that strikes a major urban area could easily exceed 100 billion dollars. This is of the same scale as the losses suffered in hurricane Katrina in 2005 (EERI, 2003).

Figure 3. A lack of knowledge about existing vulnerable structures throughout the U.S. and around the world challenges our ability to develop resilient communities.

Urban regions are diverse, complex and interdependent networks of physical systems (education, economic, health, buildings, highways, power and water grids, subways and others) and social and human systems (including schools, agencies, and social networks). In the US, even on the West Coast, urban infrastructure systems are often more than a century old. Thus, many existing buildings and infrastructure assets do not conform to modern seismic design standards. Based on current rates of replacement or repair, today's built environment will continue in use well into the 21st century. The challenges to community resiliency presented by the uncertainties regarding the actual building and infrastructure inventory and its condition, the costs of current mitigation techniques, and the limitations of existing tools for making decisions about renewal strategies, make the implementation of large-scale structural and geotechnical engineering projects aimed at revitalization to increase resilience one of the grand engineering challenges for

Figure 4. Demolition of collapsed building and watering down of burned area, October 18, 1989, Beach and Divisadero Streets, Marina District after the October 17, 1989, Loma Prieta CA Earthquake (C.E. Meyer, U.S. Geological Survey).

the 21st Century (NAE, http://www.engineeringchallenges.org/).

This research theme tackles an important and challenging problem of our aging built environment from the standpoint of increasing its resilience in a sustainable, cost-effective and timely manner. To address the renewal of the built environment, engineers and scientists need tools to accurately assess the seismic hazard, including the possibility of early warning of impending earthquake. To assess the risk exposure, improved built environment inventory techniques for management of large databases, and technologies to efficiently survey, sample and assess the condition of these large inventories need to be developed. Advanced computational models, calibrated using data from both field and large-scale laboratory tests, and run on the latest cyberinfrastructure, are needed to identify the built environment elements that contribute the most to community risk exposure. Similar simulations and tests are needed to proof-test engineering solutions for sustainable revitalization of aging infrastructures. Using this information, public policy planners and owners can rationally prioritize risk mitigation expenses and conduct an informed renewal of the built environment.

Existing vulnerable buildings and infrastructure assets are the number one seismic safety problem in the world today.

A crisp example of the need is represented by the ever increasing inventory of aging lifelines such as water supply systems. Water is a critical survival resource, even slight damage to pipelines can impede combating possible fires (Figure 4) after an earthquake and can result in contamination and epidemic outbreaks.

Many pipelines are underground presenting an additional challenge to the critical steps of inventoring existing condition as well as to the assessment of the damage after an earthquake. This fact requires innovative technologies for inspection and evaluation of the vulnerability of the entire system. Improved resilience of this system could be enhanced by improvements towards making the pipelines smart structures, where the material used in the structure could be used as a sensor to detect damage (Figure 5).

Figure 5. Damage detection and health monitoring of buried pipelines ongoing NEESR project conducted at the NEES@Cornell Equipment Site by University of Michigan (Prof. R. Michalowski, PI), and researchers from Purdue University, Virginia Tech, and Merrimack College).

Owing to the vastness and age of the inventory, unique solutions that accomplish the multiple objectives of repairing and strengthening in an economic and expeditious manner are essential.

Intellectual Merit

The intellectual merit of renewing the built environment lies in multiple fronts. First is the multi-disciplinary challenge of having knowledge of the type, condition and distribution of the inventory in sufficient fidelity to allow reliable simulation at all scales, from the individual component to the regional level. Next, the task at hand also requires understanding the mechanics of damage at various levels including collapse under three-dimensional loading, implementing that understanding in software usable for individual system analysis, and validating the software against experimental observations. Finally, the translation of the individual physical system level understanding to the level of an urban region is needed. The intersection among engineering and social sciences, and public policy occurs at this region-scale simulation level. This is crucial, because such simulations are the only tools capable of providing a rational basis for recommending the best strategies for renewal of the built environment to increase its resilience.

Existing physical systems, many of which were built when technical knowledge was less advanced, are now being challenged to perform to modern standards and are in need of renewal. This infrastructure will need to keep pace with future needs and broader goals, such as increased use and rate of deterioration, better understanding of the true hazard exposure, need for sustainable revitalization and increasing safety and security demands. Future renewal techniques must include consideration with regards to the sustainability of the solution in terms of its impact on the environment and energy consumption. These are significant engineering challenges: the benefits of engineering solutions, made to enable rational region-level renewal decision making, clearly outweigh the costs.

Broader Impacts

The broader impacts of the renewal program are extensive. The research tackles an important and challenging problem that will advance discovery and understanding of earthquake engineering, serve as a model for other hazards, and provide a comprehensive and sustainable solution to the problem of our aging built environment. Through the integration of research and education components, a commitment to teaching, training, and learning at multiple levels will be demonstrated. The educational activities should expose a diverse population of undergraduates to the critical area of renewal of the built-environment in a sustainable way and promote top candidates into graduate research. The results will benefit society through the means noted above, most directly by helping define appropriate engineering and public policy solutions to address the problem of renewal of existing infrastructure. By better understanding collapse of buildings during earthquakes, we also will contribute to knowledge on vulnerability and toughening of infrastructure against effects of explosive and impact hazards addressing a national security issue. Renewal strategies developed for earthquakes can also inform strategies for other natural hazards such as hurricanes.

> *Existing physical systems, many of which were built with performance expectations different than current ones when technical knowledge was less advanced, are now being challenged to perform to modern standards and are in need of renewal.*

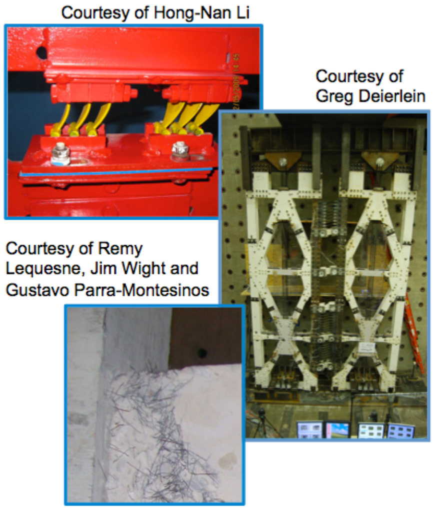
Tools Needed and Role of NEES Facilities

To energetically attack the significant challenge posed by the aging built environment, a number of tools, some existing and some that will have to be developed, systems for renewal, and partnerships between scientists, engineers, and social scientists are needed. The tools cover a broad range, spanning from modeling, physical simulation, computational simulation, to design, repair and revitalization, and to real-time monitoring, behavior data archival, education and information dissemination.

The activities in the area of renewal of our built-environment will take full advantage of the state-of-art capabilities of the NEES collaboratory and by utilizing its data archiving, physical simulation, computational simulation and collaboration infrastructure will contribute to its development. The results of the program will be disseminated in several ways, including: by sharing results using the NEES cyberinfrastructure resources; by involving earthquake professionals, social scientists, educators and urban planners; and by disseminating educational materials.

New Materials and Structural Systems

For the 2020 Vision of resilient and sustainable communities, structures and civil infrastructure will benefit greatly from developments of new materials and new technologies to engineer new or re-engineer old structural systems to improve their performance, increase their lifetime and reduce their load on the Earth's resources. New materials, components and structural systems are those that have not been commonly used in modern earthquake engineering, or such combinations of common materials, components, systems and technologies that have not be attempted to date. It is essential to recognize that new materials and technologies cannot be successfully deployed alone: instead, a new material necessitates a re-design of the components and the system; similarly, a new system may benefit greatly from the superior performance of a new material or technology.


Courtesy of Hong-Nan Li

Courtesy of Greg Deierlein

Courtesy of Remy Lequesne, Jim Wight and Gustavo Parra-Montesinos

Figure 6. New materials and structural systems should be considered for the development of resilient cities.

Common structural materials: steel, wood, masonry, concrete (a cement-stone composite) and soil are plentiful (thus, inexpensive), and relatively light, strong and stiff. Two research directions are identified: 1) improvement of existing materials; and 2) development of new materials. The first research direction involves starting with the existing, well-known materials, and pushing their properties in desirable directions. The second research direction aimed at developing new materials starts with a description of desirable properties, most likely in terms of mechanical characteristics and durability, followed by a targeted development of new synthetic materials that meet or exceed the stated design requirements. Such new materials may be passive, or may be conceived with sensing and actuation capabilities giving them an auto-adaptive property (Frosh and Sozen, 1999). A newly developed material should be characterized to enable the us of physics-based models to evaluate mechanical response, durability and sustainability of the structures built using it.

Development of new structural technologies is seen as moving on a research track paralleling that of new materials. In fact, significant cross-links between new materials and new technologies are identified. Today, resilent structures are benefiting from material developments that enabled reliable and durable elastomeric and friction-sliding seismic isolators. Tomorrow, new ways to modify the response of structures, through rocking, or through the use of active or semi-active response modification devices, will make use of new materials. An increasing role of cyber-physical systems in new resilient structures is anticiapted: research efforts to understand the dynamics of controlled structural systems, to develop and validate cyber-physical response modification technologies, to introduce them into design practice are needed.

New, resilient, structural components and systems involve strategic deployment of new materials and technologies. Modular structures, engineering structural systems that are built using pre-fabricated components or structural response fuses, and assembled in an accelerated manner, are identified as a paradigm for future resilient structures. Modeling of such structures requires multi-scale and multi-physics modeling and high-performance computing, visualization and data processing capabilities. These models and tools enable simulation of the entire life-cycle of a structure, from the material and component production stages, through construction, service life, including renewal cycles, extreme events and its final de-construction. Validation and verification of such integrated simulation models is necessary, but challenging because of the diversity in length and time scale of the processes involved in the simulation.

A new structural materials and technologies grand challenge project is identified as the best way to initiate work on new resilient and sustainable structures. The challenge is to develop materials and technologies that will shift the paradigm of structural engineering form preventing collapse to providing high resilence through the life-time of a structures.

NEES cyberinfrastructure resources can be used to develop the data structures and visualization methods needed to enable effective simulation of new resilient structures.

Intellectual Merit

Development of resilient and sustainable structures using new materials and structural systems involves a diverse and wide array of engineering disciplines and requires fundamental science. It is clear that structural engineers will have to cooperate closely with materials scientists and mechanical engineers, with computer scientists and experts in cyber-physical systems, as well as architects and community planners to achieve the research goals identified above. The broad cross-disciplinary nature of such collaborations generates the tremendous intellectual merit of research in this area. Another meritorious aspect of research in this area is the vertical collaboration between developers, owners, designers, constructors, inspectors, users, insurers and community governance stakeholders centred around the concept of resilence of communities. Intellectual merit of such integration is in understanding the interaction that span far out of the engineering field into social sciences, public policy and finance.

Broader Impacts

The broader impacts of research on new materials and technologies for resilient and sustainable structures are in expanding the reach of earthquake engineering into other engineering disciplines, as well as beyond engineering into fundamental and social sciences. Today, the challenges that drive fundamental science and development of new materials and technologies come from new medical, energy and high-technology applications. Re-focusing the view on society-level earthquake resilience, a goal of great importance but insufficient visibility, through the emphasis on sustainability, improvement of individual quality of life through risk reduction, and betterment of society through risk-balanced deployment of resources is key to garnering science and engineering talent for research in this area.

Tools Needed and Role of NEES Facilities

NEES facilities can be used to develop new materials and structural technologies and to determine the behavior of new modular and cyber-physical structural systems. Furthermore, NEES cyberinfrastructure resources can be used to develop the data structures and visualization methods needed to enable effective simulation of new resilient structures. Finally, NEES access to national high-performance computing resources will facilitate resilence simulations.

However, NEES facilities were not built to examine material properties at small size (from micro to nano), to examine aging, and to examine resistance of materials and components to hazards other than earthquakes ground motion, nor were they built to enable prototype synthesis of new materials using chemical or high-energy physical processes. Such facilities do exist in other engineering and fundamental science departments on university campuses and in national laboratories. It is likely that new alliance, between NEES and similar collaboratories in other engineering and fundamental science areas (e.g. NSF-supported Materials Science Engineering Research Centers) needs to be established to enable cross-disciplinary collaboration to develop new materials and technologies for new resilient structural systems. Work on these alliances should start early to precede a large scale funding effort in this research area..

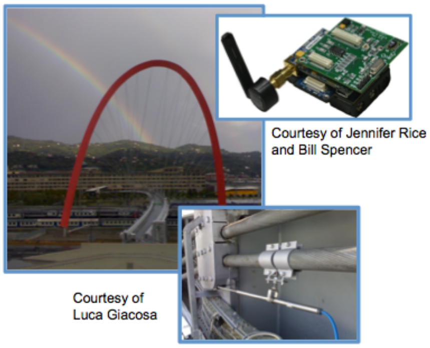
Monitoring and Assessment

Significant improvements in the resilience of our communities will also be achieved by 2020 through innovative use of data acquired through real-time monitoring of the built and natural environments. Ongoing developments in sensor technologies are leading to the possibility of introducing ubiquitous, low-cost, low-energy sensors for monitoring and assessment purposes. Components (buildings, bridges, lifelines, utilities) and systems (communities, regions, oceans, interacting networks) will be instrumented for multiple purposes. Networks of sensors may be used to appropriately measure and monitor event initiation, human responses, ocean conditions, infrastructure conditions, etc., and data acquired from the large number of sensors will offer new opportunities to obtain useful information for decision making. Data acquired may be suitable for a variety of uses such as post-event response planning, model validation, event detection, model updating, real-time diagnostic systems, etc.

In implementing such systems, vast amounts of data would be collected before, during or after an event. Thus, appropriate algorithms to reduce, digest and aggregate such data are crucial to their use. Aggregation and interpretation of the data can be envisioned for a variety of purposes. For example, decision-makers may need to access specific data during an event to aid response and recovery efforts, researchers may need to use raw data from specific structures for model validation and updating, and policymakers may use aggregated data to set regulations for the protection of the general public. Therefore, data aggregation techniques must be developed in parallel with the technologies, and the sensor networks themselves may need to be designed specifically to best implement the approaches that are found to be most effective.

Networks of sensors may be used to appropriately measure and monitor event initiation, human responses, ocean conditions, infrastructure condition, etc., and data acquired from the large number of sensors will offer new opportunities to obtain useful information for decision making.

Methods that integrate the latest real-time data to update simulation models and make informed decisions are likely to provide the most useful information during an event. However, techniques to identify suspicious results and verify current conditions are clearly needed. Furthermore, a monitoring and assessment system will often have a need for an information management framework designed specifically to meet the needs of that system.



Courtesy of Jennifer Rice and Bill Spencer

Courtesy of Luca Giacosa

Figure 7. Instrumentation of the built and natural environments will provide useful real-time data.

Intellectual Merit

This vision for the future of monitoring represents a systems level approach that will revolutionize the manner in which we understand and interact with our environment and how society responds to hazardous events. To achieve this goal, it will be necessary to advance and integrate existing methodologies into a monitoring and assessment framework and also to develop new technologies (sensors, sensor networks, materials, information management systems, models, algorithms and methodologies) that can be integrated seamlessly with the collective framework.

The availability of quality data and the information made available through this data will be useful to a large cross section of society for many purposes. The data collected will form the basis for validation of physics-based simulations. Information technology and data processing tools will be developed to ingest, manage, digest, archive and distribute the vast amount of data gathered in ways that end-users will be able to use. Practicing engineers will use such data for understanding structural behavior and validating models. Decision-makers will use the information resulting from this data for managing extreme events. Social scientists will use the data for better understanding human behavior and developing models needed to simulate human responses.

Broader Impacts

The availability of appropriate monitoring hardware systems and in combination with methods and software to acquire and manage knowledge using the acquired data offers opportunities to greatly improve the resilience of our society. Stakeholders will be provided with information to make informed decisions prior, during, and after major events. The developed capabilities will result in a safer and more resilient society, and may influence the way society is organized.

Tools Needed and Role of NEES Facilities

Both new and existing facilities will be necessary to validate emerging sensing technologies and to validate information management frameworks suitable for monitoring and assessment. Particularly, the NEES facilities provide unique capabilities for component level testing, and payload experiments are a particularly valuable mechanism for projects related to the validation of monitoring and assessment systems. However, new types of facilities involving advanced simulation capabilities integrated with numerical models are required for a systems level validation. For instance, hybrid simulations that combine experimental components with extensive numerical models of the environment (including the built environment, as well as humans, agencies, among others) will allow for the validation and assessment of strategies for better response management.

New types of facilities involving advanced simulation capabilities integrated with numerical models are required for a systems level validation.

Existing sensor networks include instrumentation on certain infrastructure or sensors distributed over large geographical regions of interest. For instance, several countries and regions have strong motion monitoring systems which collect regional information using a network of spatially distributed sensors (e.g., ANNS, GSN). NSF has other relevant programs such as the Ocean Observatories Initiative (OOI) that focuses on integrating several ocean monitoring systems to achieve a network of interacting nodes. And across the world we are able to access GPS systems for navigation. There are also a select number of existing networks include instrumentation on certain infrastructure systems. However, the ability to create linkages between such sensor networks should be further explored.

Enabling technologies for such advances in monitoring and assessment include more powerful handheld, portable computing capabilities; faster and more reliable wireless networking; advances in smart sensors with on-board computational capabilities; batteries with extended lifetimes; development of reconfigurable and self-organizing sensor networks; technologies and algorithms that can identify the severity and location of damage; new materials that can sense and resist damage; and, hybrid testing capabilities to integrate complex systems into a single simulation.

Additional tools and techniques are required to convey the large amount of data acquired, and in an understandable and useable format, to researchers and end-users. Advanced visualization capabilities are crucial to the adoption of these technologies by end-users, for example for infrastructure management and emergency response. Furthermore, the general public may be interested in acquiring information in a useful format for personal uses. For instance, an individual might be interested in knowing the condition of a structure before purchasing a house or condominium.

This vision would best be achieved through the development and use of testbeds, demonstration projects, and benchmark studies dedicated to the validation of new techniques and technologies and to demonstration to end-users. Additionally, testbeds would make it possible for sensor technologies and techniques to be compared side-by-side, facilitating identification of the performance and limitations inherent to various approaches. There are currently very limited testbed facilities available for researchers, and more are clearly needed.

Simulation of Systems

Simulation is a central component to improving the resiliency of the built and natural environments to hazards such as earthquakes and tsunamis. The term natural and built environments refers to the natural and human-made surroundings that provide the setting for human activity, ranging in scale from personal shelter and buildings to neighborhoods and cities, and can often include their supporting infrastructure, such as water supply, transportation, or energy networks. From a system of systems perspective, the natural and built environments represent a set of interdependent infrastructure systems that involve some form of dynamic behavior, where parts of the complete system have state conditions that vary independently over time. There has been extensive work in the modeling of some of these systems. However, its application to evaluate their resiliency to earthquake and tsunami hazards has been limited due to the intrinsic complexities and interdependencies involved.

Simulation of systems includes developing and utilizing interacting models for the study of interacting elements of the built and natural environments.

The ability to simulate the behavior of infrastructure systems, including both their long-term degradation as well as response to extreme events, is the essential enabling technology for achieving the 2020 vision of resilient and sustainable communities. Simulation can refer to numerical simulation, but more broadly in the earthquake engineering community it encompasses physical and computational simulations, as well as hybrid simulations involving both.

Accurate numerical simulation of individual components (buildings, bridge, traffic, humans, etc) has been a focus of the research for several decades. However, simulations that consider "simulation of systems" should be the focus of future research efforts. Simulation of systems includes developing and utilizing interacting models for the study of interacting elements of the built and natural environments. These include the development of appropriate multi-scale and multi-physics models, as well as hybrid experiments using current and future NEES facilities and tools. For example, in the context of earthquake hazards the interacting elements include the fault-plane rupture and energy dissipation, propagation of waves through rock, soil amplification through soil layers, the structural response and its interaction with other structures, and quantification of damage and losses to society. This constitutes a system of systems where the natural environment interacts directly with the built environment. The inter-relations between the built and natural environments include manifestations of the physical and social infrastructures and their connection to the environment. The need for the capability to run such hybrid simulations is clear.

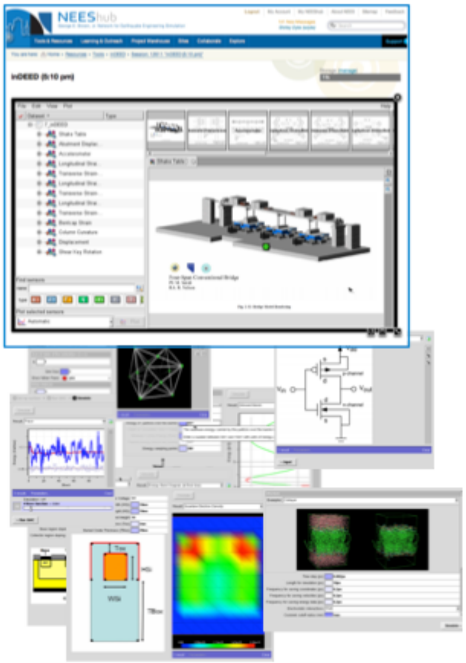


Figure 8. The ability to perform simulations at a systems level is essential to improving resiliency of our communities (hubzero.org/).

"Simulation of systems" includes both development and utilization of tools for the study of interacting elements of the built and natural environments ranging in scale from simple buildings, to complex systems including transportation systems, water supply or energy networks. The simulation tool development process comprises theoretical advances in both modeling of physical and chemical processes in the built and natural environment and computational advances in numerical simulation tools and platforms that host the models. Utilization of the new simulations systems is predicated by their verification and validation by comparison to results of carefully designed physical experiments that include both separate effects of model components and integrated effects reflecting the behavior of the systems. Examples that offer aspects of considering the resilience of urban communities as a system of systems are presented on web sites urbansim.org and openhazards.com.

A merger of the experimental and numerical simulations, an extension of the hybrid simulation concept pioneered in NEES, is a natural extension of the resilient system simulation.

However, simulation of the interaction of earthquakes and tsunamis with physical systems found in the natural and built environment is necessary, but not sufficient to achieve actual resilience at the community or society level. The interface of human social systems with the physical environment is where the true cost to society is felt and negotiated. The concept of "risk" is socially defined. Policy makers and practitioners are always seeking common ground to understand risk and prioritize mitigation activities. Social systems play a role in the distribution of risks born by different sectors of our communities. It is in this nexus of engineering and social policy where such things as building code modification, and funding for public education, prevention and mitigation programs are negotiated and enacted.

Simulation of the effects of earthquakes and tsunamis on the human community is key to garnering the political will to take action appropriate to that community. Thus, social system features should be modeled based on theoretical foundations and tested empirically, then integrated with the engineering system models for testing. Just as seismic risk varies by geography and characteristics of the built environment, the social systems that govern things such as perception of risk, or political will to implement code changes, or to invest in mitigation projects vary by community. Understanding the social structures that mitigate or exacerbate community risk is equally important to understanding how the built environment will respond to an earthquake. Once these social structures are known, they can be created and nurtured within a community to transform the potential risk reduction offered by engineering research into actual community resilience.

Intellectual Merit

Future design, building and use of resilient and sustainable systems and communities require high-fidelity tools for simulation of such system. The principal challenge is the development of simulation tools able to identify sources of disruption of system function that is not possible by studying individual system elements. To achieve this goal, the physical and numerical simulation of the system must capture the interaction of the constitutive elements in addition to correctly simulating the elements themselves. There is significant intellectual merit in developing a generic system simulation engine that transcends its application to resilient infrastructure system. Going a step further, such system simulations will help reveal the sources of uncertainty that have the most impact on the uncertainty of the system behavior predictions.

Simulation of the effects of earthquakes and tsunamis on the human community is key to garnering the political will to take action appropriate to that community.

Development of a system simulation tools to study resilience should include development of methods that will extend the range of spatial and temporal scales that can be simulated in a single, combined, simulation. Multi-scale modeling capability is essential for the next step in this direction: use of simulation to gain insight into the physical and chemical phenomena and interactions beyond those gained from experimental observations alone. In fact, a merger of the experimental and numerical simulations, an extension of the hybrid simulation concept pioneered in NEES, is a natural extension of the resilient system simulation. A significant outcome of such efforts will be an identification of gaps in the existing experimental data that need to be filled to provide for the validation and verification of the simulation codes.

Broader Impacts

Among the seven research directions identified by the participants of this workshop, simulation of systems has the highest potential to broadly impact other engineering disciplines, the sciences, public policy, and, most importantly, society itself. Identification of weak elements and their links in infrastructure systems will lead to their re-engineering and, thus, increase in resilience. In a broad sense, this engineering exercise will inform the public policy makers and the public in general about the risks posed by the built infrastructure. Accessibility to engineered system simulation tools will serve as an incentive to augment them using modeling tools from sciences, economics and public policy to build tools that enable society-level assessment of interrelations between the natural and the built environments and evaluation of societal risk exposure.

Tools Needed and Role of NEES Facilities

Several tools are required to develop the capabilities needed to perform these types of simulations. For the computational components, finite element analysis, computational fluid dynamics, particle-based methods, multi-physics modeling, etc. all will play a role in such complex simulations of urban systems. Also, performance based design of structural and geotechnical systems involves parametric studies, Montecarlo simulations and evaluation of responses for multiple motions at multiple hazard levels, requiring high-end and distributed computing capabilities. Software is needed with the capability to simulate complex systems including the interaction between physical and social infrastructures. One approach is to build an entirely new tool that makes it possible to perform simulations of these complex systems. An alternate approach is to build complex simulations using the fundamental tools for each of the current components of these systems. Both of these possibilities offer a solution but the most appropriate path forward should be considered. Independent of the approach, it is clear that large-scale simulations will be needed to study such systems, and extrapolation of current software development indicates simulation of complex systems is attainable.

Cyberinfrastructure that will facilitate data collection and management to enable rapid and efficient access and distribution of experimental and simulated data will be essential.

For the physical component of these systems, current NEES sites and computational resources will need to be employed. However, new testing capabilities will be needed for improved physical and numerical simulation. Laboratory facilities suitable for full-scale (or near full-scale) testing of elements are needed. Physical tests should be motivated by output from systems level numerical modeling. Areas of interest should include, but not be limited to, fluid-structure and soil-structure systems, as well as the combination of them. Furthermore, accurate sensors and high capacity portable loading systems are needed for full-scale testing (including large deformations and collapse) of existing structures will be required.

Cyberinfrastructure that will facilitate data collection and management to enable rapid and efficient access and distribution of experimental and simulated data will be essential.

Data collection and distribution of large and diverse data sets is currently performed in many fields including civil engineering. Its application to the simulation and analysis of the built and social environments in the context of earthquake hazards is attainable with current resources.

High performance computing (HPC) capabilities will also be needed for the analysis of complex systems including interacting systems from the built and natural environments and the implementation of performance based design methodologies that will require thousands of simulations of a given system. Current trends in the development of HPC indicate simulation of the interacting elements of the built and social environment can be achieved in the near future.

Research focusing on the simulation of systems requires the integration of the outcomes of all of the previously mentioned research directions, and is critical for the acceptance of newly developed approaches. Currently there is a severe gap in our ability to perform accurate and reliable physical and computational simulation of these complex, interacting systems, and thus in achieving the 2020 Vision.

Implementation and Technology Transfer

To have a measurable impact on resilience, the research proposed within the previously discussed 2020 Vision directions must be implemented, and the technologies developed must be transferred. More specifically, this requirement encompasses: i) implementation of earthquake engineering research (e.g., the previously discussed research directions) in engineering practice, as well as public policy and decision making; ii) two-way transfers of technology between earthquake engineering and earthquake science, engineering for other natural and man-made hazards (e.g., hurricanes and carbon emissions), and the public and other stakeholders and decision makers; and iii) understanding the social systems that govern the perception of risk, and that mitigate or exacerbate community risk, and nurturing these systems to transform opportunities provided by engineering research into actual community resilience. While the importance and urgency of technology transfer is clear, the slowness with which earthquake engineering research is implemented and transferred is a common complaint.

Understanding the social structures that mitigate or exacerbate community risk is equally important to understanding how the built environment will respond to an earthquake.

Unlike the 2020 Vision research directions discussed previously, the research required to improve technology transfer is not so much earthquake engineering research as it is research on topics such as diffusion and acceleration of innovations, early adopters, encouraging change, effective communication (including social media), education (including curriculum development), and collaboration. However the direct impact on structural and geotechnical engineering is clear. This research would lead to, as examples: building codes that better take advantage of recent earthquake engineering research, as is done in implementing earthquake science research through the USGS

National Seismic Hazard Maps; building rating systems that, in effect, transfer the technology of risk modeling, once in adequately robust and objective forms, to the public; and, implementation of proven institutional features that promote community resilience.

Experts in education and communication attending the workshop did offer several suggestions for research directions and tools that could be implemented to enhance technology transfer as well as potential applications. The proposed ideas include: practitioner participation in research projects, to facilitate implementation of the research results and/or more effective transfer of the technologies developed; pilot projects focusing on schools or federal buildings, as examples of cases for which early adoption is more likely; case studies and documentation of projects that demonstrate effective deployment of available earthquake engineering research results and technology and its impact; and development of teaching materials that will promote technology transfer and serve as examples of what is needed to effectively implement and transfer earthquake engineering research.

Other tools were also suggested that should be utilized to encourage advances in implementation and technology transfer. These suggestions include: incentives for implementation such as reduced costs for earthquake-resistant construction; technology pull (or “carrots”), such as the need for earthquake risk modeling that might be used to reduce insurance premiums and/or deductibles; technology push (or “sticks”), such as cost-effective retrofit schemes that might be implemented via local ordinances; technologies transferred from other industries, such as video games and social networking; and funded and unfunded champions/leaders, such as EERI and others.

Implementation and technology transfer are intended to increase resilience in a very direct manner. The associated impacts of research on this 2020 Vision direction will include reduced implementation time, more widespread implementation in more diverse settings, and earlier adoption of technologies developed. All of these impacts will also lead to earlier and more diverse feedback on the implemented research and/or transferred technologies, based on observations and assessments.

Figure 9. Accelerating the transfer of new knowledge and technologies to practice through key organizations will facilitate realization of resilient communities.

Implementation and technology transfer is truly a cross-disciplinary research direction. Not only does it span the earthquake engineering research topics proposed within the previously discussed 2020 Vision themes, it also motivates communication, coordination, and collaboration between earthquake engineers, scientists, researchers, practitioners, decision makers, and other concerned stakeholders, including the public. More widespread implementation and accelerating the pace of technology transfer is clearly a critical step towards achieving earthquake resilience. Research on the barriers and how to surmount them is essential in achieving the 2020 Vision for resilient and sustainable communities.

While the importance and urgency of technology transfer is clear, the slowness with which earthquake engineering research is implemented and transferred is a common complaint.

Potential applications that could result from research focusing on implementation and technology transfer include: building codes that better take advantage of recent earthquake engineering research, like they do in implementing some earthquake science research through the USGS National Seismic Hazard Maps; and building rating systems (analogous to restaurant health ratings) that, in effect, transfer the technology of risk modeling, once in adequately robust and objective forms, to the public.

Role of NEES in the Achieving the 2020 Vision

The NEES collaboratory has become a global resource for a community focused on the mitigation of earthquake risk and to fulfill the NEES vision – of a global infrastructure network that improves the resilience of new and existing construction, and supports the education of the next engineers and scientists. With current NEES facilities, researchers have the capability to conduct a variety of large-scale physical simulations and relatively simple hybrid simulations, which were not possible before. Existing cyberinfrastructure of the NEES collaboratory also allows the research, education and practicing communities to ingest, preserve and access data that is useful for researchers, educators and practitioners. These facilities are making it possible for researchers to perform a new generation of experiments and do so in a collaborative environment.

Figure 10. The Network for Earthquake Engineering Simulation (NEES) facilitates innovative research and cyberinfrastructure to realize this *2020 Vision*.

Using and extending the existing capabilities of the NEES collaboratory will be essential for achieving the 2020 Vision of resilient and sustainable communities.

The NEES network is also making strides toward having an impact on engineering practice and beyond. NEES Equipment Sites are being used to support both research on and the implementation of technology transfer. The NEES cyberinfrastructure is also enabling the development of the NEESAcademy to offer interactive, online learning activities suitable in informal and formal settings. The NEEShub makes available research data, models and tools that may be repurposed within and across disciplines. Further such activities include the NEES-EERI Research to Practice eBrownbag Webinar Series, and innovative visualization capabilities integrated with data and models. While these capabilities are being designed to support earthquake engineering research and practice, clearly they are also useful more broadly.

Nevertheless, extending the existing physical and computational capabilities of the NEES collaboratory will be essential for achieving the 2020 Vision of resilient and sustainable communities. To address the renewal of existing vulnerable infrastructure and to examine the innovations possible with the new materials and new technologies discussed within this report, testing and validation through existing and possibly new NEES facilities is needed. Furthermore, an evolution of the existing cyberinfrastructure will be needed to provide new inventory capabilities, data collection and assimilation methods, and the broad range of simulation capabilities needed to support the research directions described within this report.

Several specific requirements for the NEES collaboratory were identified as necessary to achieve the 2020 Vision goals, including:

- High capacity portable loading systems are needed for full-scale testing (including large deformations and collapse) of existing structures;
- New classes of field testing equipment to enable verification of elements, models and methods at full scale (including structural, geotechnical and lifeline systems as well as fluid-structure and soil-structure systems);
- Facilities to characterize and validate new materials and new structural technologies and to determine the behavior of new modular and cyber-physical structural systems;
- Cyberinfrastructure resources to develop the data structures and visualization methods needed to enable effective simulation of new resilient structures.
- Improved capabilities to allow researchers to consider community impact, such as developments to better integrate social, physical and numerical components into simulations;
- Experimental data reported within the context of quantitative resilience metrics at the community level;
- Verified real-time data collection and assimilation methods and structural updating and assessment techniques using large-scale structural and centrifuge facilities and shake tables;
- State-of-art capabilities to support data archiving and preservation, inventory and

search capabilities, and advanced computational simulation and collaboration infrastructure;

- Enhanced capabilities for the simulation of complex systems that require multi-scale and multi-physics modeling, for instance to simulate events at a regional level;
- Access to national high-performance computing resources to facilitate numerical simulations for implementation of performance based design;
- Wikis for discussing research needs amongst all stakeholders, a virtual clearinghouse of ideas; and
- World-class facilities to enable the education of the next generation of engineers, and for accelerating the transfer of new knowledge to the practicing engineers for immediate implementation.

NEEShub
George E. Brown, Jr. Network for Earthquake Engineering Simulation

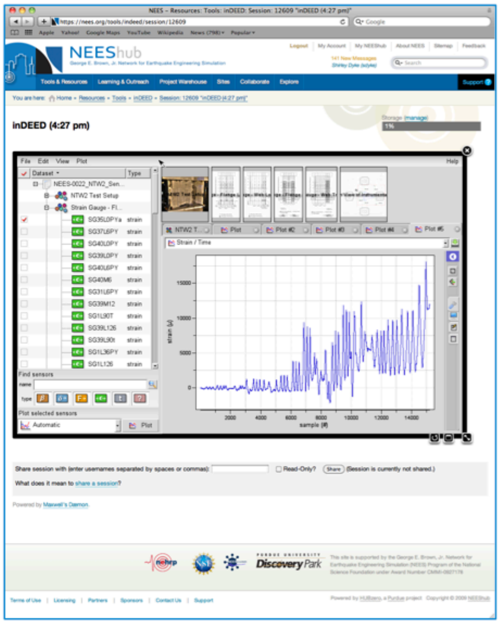


Figure 11. NEES cyberinfrastructure needs include advanced simulation and visualization tools, as well as data collection and information management capabilities (nees.org).

Several enabling technologies needed to successfully achieve this 2020 Vision were also identified in this report, and are summarized in Figure 12.

The dissemination of such knowledge by sharing data, research and learning tools through the NEES cyberinfrastructure resources; and by involving earthquake professionals, social scientists, educators, urban planners, and other will undoubtedly contribute to reducing the risks of life and property from future earthquakes and, likely, other hazards.

ENABLING TECHNOLOGIES TO ACHIEVE THE 2020 VISION

Early warning systems – real-time measurements will be essential to inform infrastructure response prediction.

Seismic hazard assessment techniques – pre- and post-event, regional-level techniques that can evaluate the condition of a community and inform rescue operations.

Infrastructure inventory techniques – understanding the existing inventory and its current state is needed for quantifying the resilience of a community and for prioritizing rehabilitation efforts.

New smart sensor technologies – real-time data acquisition and risk assessment is needed to improve situational awareness for first responders, for structural response prediction and assessment, and to acquire data used to improve models and infrastructure inventory systems.

Innovative data collection, processing and aggregation systems – vast amounts of data will be acquired with ubiquitous sensing requiring advancing our capabilities regarding data aggregation, collection and management.

Advanced nonlinear modeling capabilities – simulation of realistic damage and collapse in structural systems for assimilation of real-time data and evaluation of the integrity of a structure.

Multi-scale and multi-physics modeling techniques – to consider the complex behaviors of new materials and structural systems, and to consider their performance over their lifecycle.

Hybrid simulation methods – the intersection of engineering, social sciences and the public policy occurs at the region-scale simulation level

High performance computing – larger, faster simulation capacity that can consider the numerous simulations needed for performance based design as well as the multi-scale, multi-physics and cyber-physical-social models that are needed for simulation of systems of systems.

Advanced decision support tools – for prioritizing risk mitigation measures, aiding first responders, and conducting informed renewal of the built environment

Communication tools – for optimal rescue and mitigation steps, as well as assessing the impact of these actions.

Research on improving technology transfer is needed to ensure that knowledge associated with the most critical physical and social components for developing resilient and sustainable communities is acted upon in a timely manner.

Figure 12. Summary of Enabling Technologies Required.

Summary

The 2020 Vision workshop was held to formulate a vision of where earthquake engineering in the US needs to be in 2020. The participants represented a diverse cross section of researchers and practitioners from the earthquake engineering community. They identified resilient and sustainable communities as the overarching goal to pursue.

Seven principal directions for future earthquake engineering research were identified:

Metrics to Quantify Resilience: Communities need to establish measureable performance goals for before, during and after an event. These metrics can guide future research efforts and inform where investment in resilience will be most effective. Thus, experiments should consider the impact on the community. High performance computing capabilities will enable faster and more advanced analyses for establishing such measures.

Hazard Awareness and Risk Communication: Real-time data collection and assimilation capabilities on a regional scale will facilitate early warning systems and infrastructure response prediction. Additionally, advanced structural analysis tools will use such real-time measured data to better gage the condition of our infrastructure systems. These technologies will lead to the establishment of better decision support tools for prioritization of funding allocations prior to an event and enhanced situational awareness of first responders after an event.

Renewal of Existing Infrastructure: Existing physical systems, many of which were built when technical knowledge was less advanced, are now being challenged to perform to modern standards and are in need of renewal. To tackle this grand challenge in earthquake engineering, advanced inventory technologies, behavior-based nonlinear modeling, and real-time assessment capabilities are needed. Furthermore, cyber-physical-social system modeling and simulation is needed to prioritize and inform decision makers. Large scale testing is needed for validation of the methods developed.

New Materials and Structural Systems: Advances in new materials and adaptive structural technologies will revolutionize our ability to develop resilient and sustainable communities. Engineered structural systems that are built using pre-fabricated components or structural response fuses, and assembled in an accelerated manner, are a paradigm for future resilient structures. Ways to modify the response of structures, through rocking or the use of intelligent devices, will make use of new materials. Modeling of such structures requires multi-scale and multi-physics models and high performance computing. This direction will involve a diverse set of engineering disciplines and fundamental science. Validation of new materials and structural systems will require testing and verification of those systems through large-scale experiments.

Monitoring and Assessment: Recent developments yielding inexpensive and smart sensors facilitates ready instrumentation of our environment at the level of a single structure or an entire region. Real-time data collected from such systems will have farreaching impact, detecting event initiation or structural deterioration, as well as informing hazard prediction models, structural assessment tools, social infrastructure models, first responders and decision makers. Combined with advanced data aggregation techniques and advanced visualization capabilities, the availability of such sensor networks will greatly enhance our ability to develop resilient and sustainable communities.

Simulation of Systems: The ability to perform simulation at a systems level (e.g. considering physical, social and cyber components) is crucial to development of resilient and sustainable communities. Hybrid simulation capabilities, extending the concept pioneered within the NEES collaboratory, are needed to consider the inter-relationships between the systems. Such advanced simulation capabilities will facilitate a wide variety of research advances, such as the study of long-term degradation (i.e. sustainability), as well as event response at the regional level.

Implementation and Technology Transfer: Research on accelerating technology transfer is required to ensure that the research outcomes related to developing resilient and sustainable communities are implemented in a timely manner. This strongly multi-disciplinary topic will require the involvement of a diverse set of researchers for developing strategies to accelerate technology transfer, and the effective communication of those strategies. The direct impact of implementing this knowledge to improve the physical infrastructure, and thus on the resilience of our communities, is clear.

It is important to recognize that the research directions identified in this workshop will not only advance discovery and understanding of earthquake engineering, it will also directly impact the resilience of our communities to earthquakes and hazards. Development and use of resilence prediction and assessment tools recommended herein will lead to improved tools for decision making prior to an event or in response to an event, enabling communities to evaluate, quantify and enhance their resilience.

Existing and new NEES facilities and cyberinfrastructure capabilities are critical for performing the research and education needed to make progress along the research directions identified. NEES will need to enhance its capabilities to provide: testing for validation of retrofit solutions, new materials and new technologies; co-located data repository and tools, including infrastructure inventory capabilities; advanced simulation and hybrid simulation capabilities to consider both physical and social systems; advanced data collection and assimilation methods. NEES will also facilitate an impact on practitioners, emergency responders and the education of our youth through dissemination and technology transfer activities. NEES must remain well positioned through its civil and cyber expertise for the pioneering research that will fundamentally alter the behavior of our infrastructure systems and the planning and operations of lifeline systems. Such a transformation of earthquake engineering will broadly impact the coming generations of students through transformative research followed by application of these innovations in practice.

Achieving the 2020 Vision will require a revolutionary change in the earthquake engineering processes typically followed to generate fundamental knowledge and develop enabling technologies. Earthquakes cannot be prevented, but their global impacts on life, property and the economy can be managed. Our civil infrastructure is already undergoing substantial changes with the integration of sensor networks, intelligent controls, smart materials and real-time health and condition monitoring. This trend will intensify, resulting in improving the efficiency and performance of these systems for future generations. Additionally, research demonstrating the cost-effectiveness of performance-based design practices, applications of new materials to reduce earthquake impacts, and improved retrofit strategies will facilitate removal of existing barriers to their adoption. Demonstrating that investments in earthquake safety can reduce losses from other hazards and improve whole-life cycle performance and sustainability will also support their widespread implementation. However, the various disciplines within earthquake engineering must work together to accelerate progress toward these highly multidisciplinary questions.

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Appendices

Open Space Technology

Open Space Technology (Owen, 2008) is a method to run meetings of any size to address complex, important issues and achieve meaningful results quickly. This approach functions best where more traditional meeting formats fail: in situations involving conflict, complexity, diversity of thought or people, and short decision-times. "Technology" in this case means *tool* — a process; a method. In this sense, OST represents a self-organizing process: participants construct the agenda and schedule during the meeting itself. OST is also a method to allow a diverse group of people to jointly address complex and possibly controversial topics. Most important, it provides the space for everyone in this group to express his or her opinion and a way for that opinion to be heard and affect the final outcome.

For an OST workshop to be successful, the participants must be motivated and must prepare. OST requires that participants come to the workshop with definite interest, but the actual agenda becomes set at the meeting. It fell upon the WPC to solicit attendees who have an interest representing the entire Earthquake Engineering community. Some metrics for selecting participants were:

1. Who is interested in applications of their models/theories/approaches/ideas in areas that are NOT in their discipline?
2. Have they thought about, or are they interested in thinking about, research challenges in terms of understanding and predicting the development of Earthquake Engineering as a discipline that addresses a complex system?
3. Most importantly, are they willing to move out of their "comfort zone" and not just push their own specific research agenda?

The selected participants were contacted by workshop organizers to inform them about the workshop theme, describe the format and introduce them to the workshop web site where the basics of the OST workshop were described.

OST meetings have a single facilitator who introduces and concludes the meeting and explains the general method. The facilitator has no other role in the meeting and does not control the actual gathering in any way. The participants in an OST Workshop, including the organizers, are equal. The facilitator only facilitates the emergence of the meeting agenda, and the progress of the discussions towards the final outcomes of the meeting. The openness of the space makes it impossible for one single idea or one single person to dominate the workshop. The agenda for an OST meeting emerges from the participants.

Agenda

DAY 1

7:15-8:00	Claim registrant badge: No on-site registration
8:00-9:00	Welcome and Workshop Introduction
	Meeting facilitator introduces the OST topic solicitation and self-organization
9:00-4:00	Breakout Sessions
	Six sessions, 55-minute each, with 5-minute breaks
11:30-1:30	Floating Lunch in the Open Space
4:00-4:45	Reconvene and reflect on the discussions
4:45-5:00	Self-organization of groups for dinner
6:00	Dinner

DAY 2

7:15-8:00	Continental breakfast
8:00-9:00	Reconvene and reset the agenda
	Workshop leaders review the workshop goal and restate desired outcomes
	Principal trends and topics; Self-organization/Voting
9:00-12:00	Morning Breakout Sessions
	Participants divided into 8 discussion groups to generate themes; Theme posters are presented; Main themes are identified and followed by discussion session
11:30-1:30	Floating lunch in the Open Space; preparation of session summaries
1:30-2:30	Workshop summary session
	Each theme is summarized and presented
2:30-3:00	Workshop Conclusions

List of Participants

Note that several workshop participants were forced to cancel because they were a part of the early reconnaissance efforts after the January 12, 2010 earthquake in Haiti.

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Matrix of Day 1 Rounds and Station Topics

Session Topics

Six sessions, 55-minute each, with 5-minute breaks

Time	Topic 1	Topic 2	Topic 3	Topic 4	Topic 5	Topic 6	Topic 7	Topic 8
9-10	Day 1. Session 1. Topic 1. System approach to Earthquake Engrg	Day 1. Session 1. Topic 2. What beyond experiments	Day 1. Session 1. Topic 3. Tsunami loads & Effects on structures	Day 1. Session 1. Topic 4. Seismic protection --- Not just the struct. engrg.'s job	Day 1. Session 1. Topic 5. Reducing seismic risk in less favoured regions of the world	Day 1. Session 1. Topic 6. Levees & dams	Day 1. Session 1. Topic 7. EQ engrg. in 2020 and how to get there	
10-11	Day 1. Session 2. Topic 1. What do engineers & practitioners want	Day 1. Session 2. Topic 2. Dreams of IT for earthquake engineering	Day 1. Session 2. Topic 3. Integrated reconn. surveys	Day 1. Session 2. Topic 4. Why is tech transfer from research to practice slow in EQ. engrg.	Day 1. Session 2. Topic 5. Damage detection & remote sensing, data collection technologies for rapid damage assessment	Day 1. Session 2. Topic 6. Resilient seismic design	Day 1. Session 2. Topic 7. Correlating damage to losses	
12-1	Day 1. Session 3. Topic 1. Costal Vulnerability to Multi-Hazards	Day 1. Session 3. Topic 2. Archiving & reuse of data	Day 1. Session 3. Topic 3. Numerical simulations for earthquake engrg.	Day 1. Session 3. Topic 4. Transformative research topics for EQ engrg.	Day 1. Session 3. Topic 5. Forecasts of not just EQs but damage & loss for the media	Day 1. Session 3. Topic 6. Experimental benchmark study	Day 1. Session 3. Topic 7. What do building owners want	Day 1. Session 3. Topic 8. Performance of spatially distributed infrastructure
1-2	Day 1. Session 4. Topic 1. Ports & Harbors	Day 1. Session 4. Topic 2. Utilizing NEES for developing countries	Day 1. Session 4. Topic 3. innovations possible through interdisciplinary collaboration	Day 1. Session 4. Topic 4. EQ engrg education in undergrad. and the third world	Day 1. Session 4. Topic 5. Low overhead solutions & grossly vulnerable building stock	Day 1. Session 4. Topic 6. EQ. early warning & how are we going to use it	Day 1. Session 4. Topic 7. Widespread instrumentation to validate seismic design	Day 1. Session 4. Topic 8. EQ engrg. applications for school buildings
2-3	Day 1. Session 5. Topic 1. Performance-based assessment of Earthquake carbon foot print		Day 1. Session 5. Topic 3. Effective earthquake engrg. education & how to make earthquake engrg exciting to kids, NSF	Day 1. Session 5. Topic 4. Human impacts of policy	Day 1. Session 5. Topic 5. Advancement and Implementation of seismic protective systems	Day 1. Session 5. Topic 6. Tall buildings data & models	Day 1. Session 5. Topic 7. Risk management tools for small organizations	Day 1. Session 5. Topic 8. Moderate seismic design
3-4	Day 1. Session 6. Topic 1. Performance assessment for design	Day 1. Session 6. Topic 2. Simulations of large earthquakes (no data) & Struc. resp. prediction	Day 1. Session 6. Topic 3. New Materials	Day 1. Session 6. Topic 4. What is damage, how much is too much	Day 1. Session 6. Topic 5. What are our needs in experimental testing		Day 1. Session 6. Topic 7. Lifelines interdependencies & impact on recovery	

List of Topics Proposed

1. Need for simulation attention and resources
2. Instrumenting structures
3. Researchers and practitioner collaboration
4. Low-tech rehabilitation solutions
5. Improved communications of risk to general public and stakeholders
6. Integration of social science and behavioral science (to be effective)
7. Adopting stochastic analysis methods
8. More input of Earthquake Engineering community to reconstruction after Earthquake
9. Reducing vulnerability in developing countries through education and outreach
10. Be more specific about performance objectives
11. More incentives and varieties of funding resources to encourage research-practice interaction
12. Community archiving and sharing data
13. New materials means new systems
14. Testing non-engineered construction
15. Understanding economic drivers
16. Performance objectives suitable for moderate seismicity regions
17. Need for systems level models/approaches/simulations/designs
18. Database of structural models and soil models
19. Development of physical model instead of empirical models
20. To perform test in the full scale
21. Simulations that drive experiments
22. Green engineering (e.g. capturing carbon footprint of the structures)
23. Using earthquake early warning for deploy-able structural systems
24. Realistic seismic hazard
25. Information about existing Infrastructure
26. Automatic metadata extraction from data
27. Multi-disciplinary approach to reduce hazards for school buildings

Below are newly added topics on day 2

28. Simulations (for all types, large scale, prediction)
29. Collapse of Structures
30. Systems modeling
31. Human-physical system interaction
32. Nuggets for public (translating)
33. New materials
34. Personal risk meter

35. Resilient community performance goals
36. Outreach & research through social network
37. Retrofit problem
38. "Zero" damage
39. Multi-hazards approach
40. Early warning system uses

NSF

NEES

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