Advisory Committee on Earthquake Hazards Reduction
National Earthquake Hazards Reduction Program

September 30, 2021

The Honorable James K. Olthoff, Ph.D.
National Institute of Standards and Technology
100 Bureau Drive
Gaithersburg, MD 20899-1000

Dear Dr. Olthoff:

The Advisory Committee on Earthquake Hazards Reduction (ACEHR) is authorized by Section 103 of the National Earthquake Hazards Reduction Program (NEHRP) Reauthorization Act of 2004 (Public Law 108-360), 42 U.S.C. § 7704(a)(5), and was established pursuant to the Federal Advisory Committee Act, as amended, 5 U.S.C. App. ACEHR members are non-Federal employees serving three-year terms from research and academic institutions, earthquake-related professions, and state and local governments. We are charged with assessing trends and developments in the science and engineering of earthquake hazards reduction; the effectiveness of NEHRP in carrying out its statutory activities; any need to revise NEHRP; and the management, coordination, implementation, and activities of NEHRP.

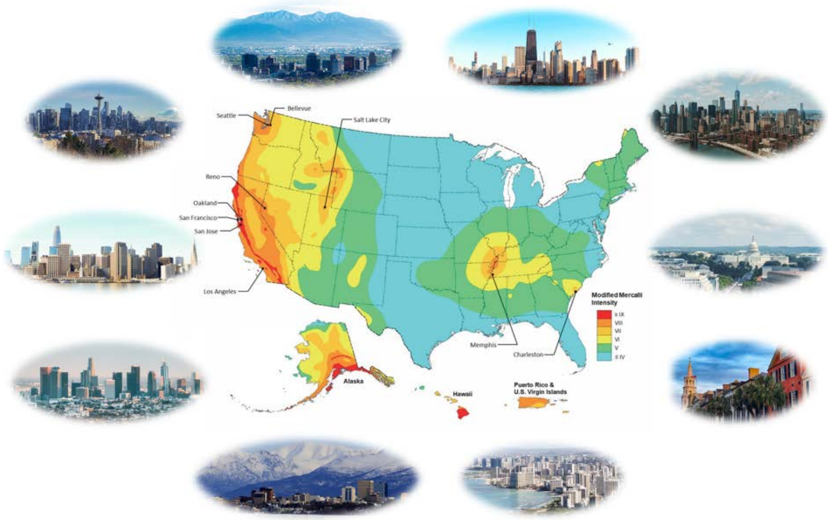
The enclosed report is submitted to you, as the Acting Director of the National Institute of Standards and Technology (NIST) and as chair of the Interagency Coordinating Committee on Earthquake Hazards Reduction (referred to in this report as the "Interagency Coordinating Committee"). Our recommendations are also directed to the NIST NEHRP Office and the four NEHRP agencies—the Federal Emergency Management Agency (FEMA), NIST, National Science Foundation (NSF), and U.S. Geological Survey (USGS).

Submitted on behalf of the ACEHR members who fully endorse these comments.

Respectfully,

Glenn J. Rix, PhD, PE
Chair
Advisory Committee on Earthquake Hazards Reduction
National Earthquake Hazards Reduction Program

Enclosure



ACEHR REPORT ON NEHRP EFFECTIVENESS FY20 - FY21

A Report from the Advisory Committee on Earthquake Hazards Reduction

September 30, 2021

Table of Contents

On the cover: Image courtesy of Ryan Kersting, Buehler Engineering, Inc. based on a seismic risk map developed by the U.S. Geological Survey

EXECUTIVE SUMMARY

Despite the significant progress toward earthquake risk reduction since the National Earthquake Hazards Reduction Program (NEHRP or Program) was originally enacted in 1977, earthquakes still pose a substantial threat to the United States. The NEHRP Reauthorization Act of 2018 (Act) is an important opportunity to build on NEHRP's 40-year record of achievement. The updated Strategic Plan as required by the Act is an important opportunity for the Program agencies (FEMA, NIST, NSF, and USGS) to develop specific and measurable goals that will advance efforts to address earthquake risks. The NEHRP agencies have made significant progress during the past two years in developing the FY22-29 NEHRP Strategic Plan. Once the Plan is approved and adopted, the focus will change to ensuring the Plan is implemented. The Advisory Committee on Earthquake Hazards Reduction (ACEHR) calls upon the NEHRP Interagency Coordinating Committee (ICC) to provide the resources required for full implementation of the Plan, including appropriations and budgetary mechanisms that are closely aligned with the Plan at agency and sub-agency levels.

ADVISORY COMMITTEE ON EARTHQUAKE HAZARDS REDUCTION

The Advisory Committee on Earthquake Hazards Reduction (ACEHR) provides a biennial assessment of the National Earthquake Hazards Reduction Program as required by the committee charter and Public Law 108-360 as amended. ACEHR is charged with assessing (1) the effectiveness of NEHRP in performing its statutory activities and any needed revisions; (2) the management, coordination, implementation, and activities of NEHRP; and (3) trends and developments in the science and engineering of earthquake hazards reduction.

ACEHR's FY20-21 biennial assessment focuses on the significant progress made by the NEHRP agencies on specific initiatives related to earthquake hazard, mitigation, response, and recovery, as well as via collaborative efforts such as the FY22-29 Strategic Plan and ICC. Our assessment includes summaries of agency progress, additional needs related to functional recovery and community resilience, early earthquake warning research, and the basic earth science, engineering, and social science research needed to support NEHRP's mission. We also highlight four related topics and issues—learning from the COVID-19 pandemic, multi-hazard approaches, climate change, and data-driven models and new sensing technology—that have significant potential to yield lessons that could benefit earthquake risk-reduction efforts and improve community resilience.

Finally, ACEHR offers seven observations and six recommendations related to the items listed above for consideration by the NEHRP agencies. The Committee believes these observations and recommendations will help address the significant risks posed by earthquakes to our nation and its citizens.

INTRODUCTION

The NEHRP Reauthorization Act of 2018 (PL 115-307 or the Act) is an important milestone for the nation. Since NEHRP was originally enacted in 1977, there has been significant progress by each of the NEHRP agencies (NIST, FEMA, NSF, and USGS) toward advancing the objectives of the Program. As a result, the earthquake community has made considerable strides in understanding earthquakes and reducing earthquake risk through basic and applied research on earthquake processes and earthquake engineering, hazard mapping, improved design and construction practices, stronger building codes and standards, public education, and community-based emergency response programs, among other activities (NRC, 2011; Leith, 2017).

The benefits derived from the federal investment in earthquake hazard mitigation far exceed the costs. A recent study by the National Institute of Building Sciences found that federally funded earthquake hazard mitigation grants between 1993 and 2016 saved society $5.7 billion at a cost of only $2.2 billion—a benefit-cost ratio of approximately 2.6 to 1. The savings are due to reductions in loss of service (34%), reduced damage to property (26%), casualties (19%), and direct and indirect business interruption (21%). This 23-year period was characterized by moderate seismic activity in the United States (U.S.); the benefits to be realized in future, large earthquakes is likely many times greater. Furthermore, trillions of dollars of investments in buildings and infrastructure by state, local, and private organizations using developments from NEHRP have increased these benefits manyfold and will continue to do so.

Despite this progress, earthquakes still pose a substantial threat for the nation. All 50 states and five inhabited U.S. territories are vulnerable to earthquakes, and nearly half the U.S. population lives in areas with moderate or major seismic risk. A large earthquake in a major urban center could cause thousands of casualties, widespread population displacement and social disruption, and billions of dollars in economic losses.

The Advisory Committee on Earthquake Hazards Reduction (ACEHR) provides a biennial assessment of NEHRP as required by the committee charter and Public Law 108-360 as amended. ACEHR is charged with assessing (1) the effectiveness of NEHRP in performing its statutory activities and any needed revisions; (2) the management, coordination, implementation, and activities of NEHRP; and (3) trends and developments in the science and engineering of earthquake hazards reduction. This report provides ACEHR’s 2021 assessment and is organized to present an assessment of progress by the NEHRP agencies during fiscal years 2020-21; key initiatives where additional effort and investment are needed to continue building on progress to date; a summary of the important role of basic research to support NEHRP; and topics and issues for which lessons learned have significant potential to affect earthquake mitigation, preparedness, response, and recovery. This report also presents ACEHR’s observations and recommendations for consideration by the NEHRP agencies to ensure that NEHRP remains a vital element of the nation's efforts to mitigate earthquake risk.

OBSERVATIONS AND RECOMMENDATIONS

This section summarizes the observations and recommendations from the 2021 ACEHR biennial report in a concise format for ease of reference. The rationale for these observations and recommendations is presented in subsequent sections of this report, with observations *italicized* and recommendations in **bold**.

Observations

1. Continuing the collaborative approach used to develop the FY22-29 NEHRP Strategic Plan for future plans is strongly encouraged.

2. The NEHRP Strategic Plan should be disseminated broadly for public comment.

3. ACEHR acknowledges the recent progress in holding yearly Interagency Coordinating Committee meetings and expects that these meetings will continue, possibly using a virtual meeting format to make it easier for agency representatives, particularly agency principals, to participate.

4. ACEHR highly values the NEHRP agencies' shift to focusing on implementation of the NEHRP Strategic Plan at a programmatic rather than agency level for their reporting at ACEHR meetings.

5. Once the U.S. Government Accountability Office assessment report is completed, ACEHR proposes that a future ACEHR meeting be devoted to reviewing and discussing the findings with the NEHRP agencies.

6. ACEHR applauds the quality and quantity of initiatives by the NEHRP agencies to improve earthquake hazard, mitigation, response, and recovery over the two-year period addressed in this report.

7. Researchers and policymakers should learn from and apply lessons on the impacts and successful interventions from the pandemic to earthquake preparedness, mitigation, and recovery planning and policy.

Recommendations

1. Once the FY22-29 NEHRP Strategic Plan is approved and adopted, the focus will change to ensuring the Plan is implemented. Depending on available resources, ACEHR calls upon the Interagency Coordinating Committee to provide the resources required for full implementation of the Plan, including appropriations

and budgetary mechanisms that are closely aligned with the Plan at agency and sub-agency levels.

2. ACEHR has two recommendations related to the structure and focus of its meetings:

    a. ACEHR calls upon the NEHRP agencies to add progress updates on previous ACEHR recommendations as a regular agenda item for ACEHR meetings.

    b. ACEHR calls upon the NEHRP agencies to continue identifying synergetic programs to present during ACEHR meetings in an effort to promote inter-programmatic coordination. This recommendation is closely related to Recommendation 5 below.

3. Given the importance of functional recovery and community resilience to the nation's safety, ACEHR makes the following two recommendations related to this key initiative:

    a. ACEHR calls upon the NEHRP agencies to implement the seven recommendations in the joint FEMA-NIST report on *Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time* and move the nation forward with respect to recovery-based objectives and community resilience.

    b. ACEHR calls upon the NEHRP agencies to sponsor a multi-agency and multi-hazard workshop bringing together individuals, divisions, etc. working on functional recovery, community resilience, and related topics.

4. ACEHR calls upon the NEHRP agencies to support research in earth science, engineering, and social science to further develop earthquake early warning (EEW) capabilities and better understand how EEW can best inform protective actions. ACEHR also calls upon the NEHRP agencies to support investments in education and outreach campaigns to increase awareness and understanding of EEW.

5. ACEHR calls upon the NEHRP agencies to further undertake additional jointly funded activities depending on available resources and where synergy is applicable.

6. ACEHR calls upon the NEHRP agencies to help organize workshop(s) for the earthquake science and engineering community to explore how applying lessons learned from the COVID-19 pandemic, multi-hazard approaches, climate change,

and data-driven models and new sensing technologies can enhance earthquake risk-reduction efforts.

ASSESSMENT OF PROGRESS

ACEHR is charged with assessing the effectiveness of NEHRP in performing its statutory activities and any needed revisions; and the management, coordination, implementation, and activities of NEHRP. The following subsections provide ACEHR's assessment of progress by the NEHRP agencies during fiscal years 2020-21.

NEHRP Strategic Plan for FY2022 - FY2029

A recommendation from ACEHR's 2019 report is that the NEHRP agencies should (i) ensure that adequate resources are devoted to developing the updated NEHRP Strategic Plan required by the Act and (ii) report to ACEHR on progress toward completing the Strategic Plan. The NEHRP agencies have addressed both recommendations during the past two years. Furthermore, ACEHR members were invited to comment upon drafts of the Strategic Plan as subject matter experts. This iterative process of sharing Strategic Plan drafts is viewed positively as it engages the expertise of ACEHR members and ensures transparency and timeliness in communication. *Continuing the collaborative approach used to develop the FY22-29 NEHRP Strategic Plan for future plans is strongly encouraged.*

As of the August 10, 2021 ACEHR meeting, it was understood that a draft of the NEHRP Strategic Plan is under review by the NEHRP agencies and will be reviewed by the Interagency Coordinating Committee (ICC). *After ICC's concurrence, likely in fall 2021, the NEHRP Strategic Plan should be disseminated broadly for public comment.*

Once the FY22-29 NEHRP Strategic Plan is approved and adopted, the focus will change to ensuring the Plan is implemented. Depending on available resources, ACEHR calls upon the Interagency Coordinating Committee to provide the resources required for full implementation of the Plan, including appropriations and budgetary mechanisms that are closely aligned with the Plan at agency and sub-agency levels.

Interagency Coordinating Committee Meetings

ACEHR views regular meetings of the ICC as essential for the agencies to collaborate on critical issues in a direct and coordinated fashion. ICC meetings resumed in 2019, and a virtual meeting was held in August 2020 at which the ICC reached consensus on the outline of the FY22-29 NEHRP Strategic Plan. ACEHR understands the virtual nature of the meeting resulted in good attendance. *ACEHR acknowledges the recent progress in holding yearly ICC meetings and expects that these meetings will continue, possibly using* *a virtual meeting format to make it easier for agency representatives, particularly agency principals, to participate.* As of the date of this report, a 2021 meeting of the ICC is pending the availability of a draft NEHRP Strategic Plan for review, agency personnel appointments by the Administration, and developments on the proposed federal infrastructure initiative under consideration by Congress as of September 2021.

ACEHR Meeting Format

The 2019 ACEHR report includes a recommendation to structure ACEHR meetings around implementation of the NEHRP Strategic Plan at a programmatic rather than agency level. Using the NEHRP Strategic Plan to structure ACEHR meetings gives the agencies an opportunity to clarify how the Plan's goals continue to enable coordination, collaboration, and integration among the agencies. ACEHR meetings held since the 2019 report have focused on addressing progress toward strategic goals rather than describing individual agency activities. *ACEHR highly values the NEHRP agencies' shift to focusing on implementation of the NEHRP Strategic Plan at a programmatic rather than agency level for their reporting at ACEHR meetings.*

ACEHR also sees value in having more regular and formalized updates from the NEHRP Agencies on recommendations made by ACEHR in the committee's biennial reports. **Thus, ACEHR calls upon the NEHRP Agencies to add progress updates on previous ACEHR recommendations as a regular agenda item for ACEHR meetings.**

Lastly, ACEHR sees value in using its meetings as a forum for learning about and discussing potential applications to earthquake mitigation, preparedness, response, and recovery from diverse sources. **ACEHR calls upon the NEHRP agencies to continue identifying synergetic programs to present during ACEHR meetings in an effort to promote inter-programmatic coordination.** Suggested examples include initiatives by the U.S. Army Corps of Engineers, Federal Highway Administration, General Services Administration, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and Department of Housing and Urban Development.

U.S. Government Accountability Office Assessment of NEHRP

In addition to the development of an updated NEHRP Strategic Plan, the Act also requires the U.S. Government Accountability Office (GAO) to perform a comprehensive assessment of the extent to which the efforts of the past 40 years under the auspices of the Program have been applied to public and private earthquake risk reduction. ACEHR understands that the GAO has completed the first round of interviews with each NEHRP agency during which each agency responded to verbal questions, and that follow-up questions and interviews are ongoing at the time of this report. The GAO has also finalized its report (GAO-21-129) on EEW and the USGS Earthquake Hazards Program. *Once the* *final GAO assessment report is completed, ACEHR proposes that a future ACEHR meeting be devoted to reviewing and discussing the findings with the NEHRP agencies*.

Specific Agency Initiatives

In addition to the overarching items described above, the NEHRP agencies have made progress on the implementation of various initiatives that address earthquake risk reduction. The list below highlights several of these contributions.

- **Seismic Hazard** - The USGS produced a major update to the National Seismic Hazards Model, particularly for the central and eastern portions of the U.S. This work implemented major new research findings from the NGA-East program pertaining to reference rock ground motion models and site amplification models.

- **Functional Recovery** – FEMA and NIST jointly submitted a Special Publication (FEMA P-2090/NIST SP-1254) titled *Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time* to Congress in January 2021. This Special Publication is discussed in more detail in subsequent sections of this report.

- **Earthquake Risk Reduction and Preparedness** - FEMA's Building Resilient Infrastructure and Communities (BRIC) program supports states, local communities, native tribes, and territories as they undertake hazard mitigation projects, reducing the risks they face from disasters and natural hazards. BRIC is a new FEMA pre-disaster hazard mitigation grants program that replaces the Pre-Disaster Mitigation (PDM) program. The BRIC program's guiding principles are supporting communities through capability- and capacity-building; encouraging and enabling innovation; promoting partnerships; enabling large projects; maintaining flexibility; and providing consistency.

- **Earthquake Response and Recovery** - In November 2019, FEMA published *Post-Disaster Building Safety Evaluation Guidance* (FEMA P-2055). The report is an outcome of the Disaster Recovery Reform Act of 2018 (DRRA), which directed FEMA to prepare guidance on best practices for post-disaster evaluation of buildings by design professionals to analyze the structural integrity and livability of buildings impacted by natural hazards, including earthquakes.

- **Earthquake Scenario Studies** - FEMA co-funded the 2020 San Diego Earthquake Planning Scenario that examines the potential impacts of a M6.9 earthquake on the Rose Canyon Fault Zone. The scenario describes the regional seismic risk profile to highlight the threat of the Rose Canyon Fault Zone and the many opportunities for earthquake mitigation to make the San Diego region more resilient to seismic hazards.

- **Codes and Standards** - Efforts in the past two years have led directly to the continued development of building codes and standards intended to reduce earthquake risk:

  - In September 2020, FEMA published updated *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures (*FEMA P-2082). It presents a set of recommended improvements to the ASCE/SEI 7-16 Standard on *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, and nine resource papers on new concepts, suggested future development, and technical information in support of the recommended improvements. Under FEMA's leadership, the NEHRP Provisions are developed and evaluated through an expert-based consensus process to ensure validity and quality of the recommended new changes.

  - In October 2020, FEMA published a Fact Sheet on *Seismic Building Code Provisions for New Buildings to Create Safer Communities* that describes the history and role of codes and standards in enhancing earthquake resilience and FEMA's State Assistance Grant Program.

  - In February 2021, FEMA published a 35-year retrospective on T*he Role of the NEHRP Recommended Seismic Provisions in the Development of Nationwide Seismic Building Code Regulations* (FEMA P-2156) that summarizes major technical changes incorporated into the Provisions and provides a roadmap for continued development of the Provisions to address recovery-based resilience.

  - FEMA is providing funding for the ongoing Applied Technology Council (ATC) project on *Update of Seismic Evaluation and Retrofit of Existing Buildings Guidance* (ATC-140-1). Its purpose is to investigate and address technical issues regarding the evaluation and retrofit of existing buildings, including support of updates to the ASCE/SEI 41 standard and development of FEMA P-2006 design applications document that expands and replaces FEMA 275.

  - The FEMA/ATC Seismic Code Support Committee has supported the model codes and consensus standards development processes by providing technical monitoring of proposed seismic code changes for the 2021 and 2024 editions of the International Codes, in addition to submitting proposed changes to the model codes based on the 2020 NEHRP Recommended Seismic Provisions and other FEMA publications.

  - In March 2021, the Building Seismic Safety Council (BSSC) Symposium on 2020 NEHRP Provisions presented recommended changes to ASCE/SEI 7-16 *Minimum Design Loads and Associated Criteria for Buildings and Other*

Structures and presented a report on unresolved issues and recommended future research needs.

- The NEHRP agencies have assumed a leadership role within the Interagency Committee on Seismic Safety in Construction (ICSSC) to facilitate inter-programmatic coordination towards the goal of reducing seismic risk associated with federally owned buildings as required by Executive Order 13717.

- **Earthquake-Related Research Activities**
  - In 2020, the National Academies of Sciences, Engineering, and Medicine issued the results of consensus study on priority science questions for earth sciences. The study, A Vision for NSF Earth Sciences 2020-2030, was commissioned by NSF's Division of Earth Sciences to help guide NSF investments in the future. Several of the grand challenges in the report are directly pertinent to NEHRP priorities.
  - In January 2020, the Natural Hazards Engineering Research Infrastructure (NHERI) program published an updated science plan for natural hazards engineering. The plan outlines three grand challenges and five key research questions to address risks from earthquakes, hurricanes, and other natural hazards.
  - In 2020, NSF and NIST issued a joint NSF-NIST Disaster Resilience Research Grants (DRRG) competition to solicit proposals for fundamental knowledge pertaining to improved science-based policies, practices, and decision tools for natural disaster resilience. In addition, NSF partnered with the Department of Homeland Security to fund a track for Resilience to Natural Disasters in its Civic

NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE (NHERI) PROGRAM

NHERI is a shared-use, nationally distributed network, supported by the National Science Foundation, that provides key infrastructure for the natural hazards engineering and social science community. NHERI combines state-of-the-art experimental facilities with a computational modeling and simulation center, a convergence-science hub, and a post-event reconnaissance facility. NHERI's cyberinfrastructure provides high-performance computing and cloud-based tools to manage, share, and publish data for research and collaboration. It promotes multi-disciplinary convergence research across natural hazards and between engineering and the natural and social sciences. The community of NHERI researchers, educators, and students encompasses a large group of universities, industry and federal partners, and research institutions in the United States and abroad.

Innovation Challenge competition. This demonstrates responsiveness to previous calls by ACEHR for joint research programs. ACEHR encourages NSF to continue working with its partner agencies on initiatives similar to the DRRG and Civic Innovation Challenge programs.

- ACEHR recognizes and strongly supports NIST's research on the impact of earthquakes and other natural hazards on buildings and communities and on post-disaster studies that can provide the technical basis for improved standards, codes, and practices used in the design, construction, operation, and maintenance of buildings and infrastructure systems. In February 2020, NIST renewed a major cooperative agreement for continued support of the Center for Risk-Based Community Resilience Planning for continued development of computer and field study tools, best practices, and guidance to support research and implementation of resilience planning. By engaging with universities and other experts, this Center and related efforts allow NIST research and development to leverage the broad knowledge and expertise in science and engineering related to the impact and recovery from natural hazards.

CENTER FOR RISK-BASED COMMUNITY RESILIENCE PLANNING

The Center for Risk-Based Community Resilience Planning, supported by the National Institute of Standards and Technology, is working on the development of system-level models and associated databases to support community resilience decision making. Headquartered at Colorado State University, the center works with NIST researchers and partners at 12 universities, with experts in engineering, economics, data and computing, and social sciences. The centerpiece of the center's effort is IN-CORE—the Interdependent Networked-Community Resilience Modeling Environment. Built on an open-source platform, the IN-CORE software and databases are incorporating risk-based approaches to decision-making that will enable quantitative comparisons of alternative resilience strategies. The Center aims to provide a quantitative and science-based approach to community resilience assessment that will support a business case for enhancing disaster resilience at the community level.

ACEHR applauds the quality and quantity of these initiatives by the NEHRP agencies to improve earthquake hazard, mitigation, response, and recovery.

KEY INITIATIVES

Functional Recovery and Community Resilience

The Act includes a heightened focus on achieving community resilience and a new requirement for FEMA and NIST to jointly convene a Committee of Experts to assess and recommend options for improving the built environment and critical infrastructure to reflect performance goals stated in terms of post-earthquake reoccupancy and functional recovery time. In response, FEMA and NIST developed a plan of action in which FEMA-funded a Project Technical Panel, responsible for report development, and NIST-funded a Project Review Panel, responsible for report review. FEMA contracted with the ATC, and NIST contracted with the Science and Technology Policy Institute (STPI) to facilitate this effort. The full Committee of Experts consisted of the Project Technical Panel, with 17 outside experts and representation from all interest groups named in the reauthorization, and the Project Review Panel, with 10 outside experts and similar representation. NIST also hosted five stakeholder workshops to gather feedback.

> **FROM THE 2019 ACEHR REPORT**
>
> Functional recovery of the built environment and critical infrastructure can be viewed as a foundational element of community resilience. What might have been construed as a technical issue—for example, designing one new building that will experience minimal downtime after an earthquake—is complicated by the reality that communities include both new and existing buildings that interact with each other through the people who occupy and use them. As increasing numbers of components of the built environment and critical infrastructure are designed, built, or retrofitted to enable their functional recovery, communities should be able to respond to seismic events more effectively—in less time, with fewer resources, and at lower social, economic, and political cost.

The deliverable from this effort, the joint FEMA-NIST Special Publication (FEMA P-2090/NIST SP-1254), *Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time*, was sent to Congress in January 2021. The report includes seven recommendations: develop a framework for post-earthquake reoccupancy and functional recovery objectives; design and retrofit new and existing buildings to meet recovery-based objectives; design, upgrade, and maintain lifeline infrastructure systems to meet recovery-based objectives; develop and implement pre-disaster recovery planning; provide education and outreach on earthquake risk and recovery-based objectives; and facilitate access to the financial resources needed to achieve recovery-based objectives.

The Committee of Experts offered four actions that Congress might elect to take, or might choose to encourage other federal entities to perform: (1) support technical development, specifically the development of recovery-based regulations and policies along with practical and effective methods for recovery-based design and retrofit of buildings and lifeline infrastructure systems; (2) incentivize action (e.g., through BRIC grants) by encouraging state and local jurisdictions to adopt recovery-based codes and standards, and engage in recovery-based planning, mitigation, financial, and other enabling activities (e.g., including references to recovery-based objectives in hazard mitigation plans); (3) encourage the Executive Branch to develop recovery-based seismic design and retrofit requirements for federally owned and leased buildings; and (4) lead the development and implementation of a federal education campaign around earthquake risk and recovery-based objectives and support similar educational efforts by state and local jurisdictions.

Part of the challenge associated with crafting recovery-based objectives is the need to determine which community functions and services (and therefore, buildings and infrastructure) are more or less essential to communities' response to and recovery from a disaster. The answer cannot be "everything," as communities must choose how to prioritize their limited resources. That communities must grapple with this practical challenge may be one of the most striking lessons from the COVID-19 pandemic. While most communities accepted healthcare workers, teachers, construction workers, farmers and food packaging workers, grocery workers, sanitary service workers, and delivery drivers as "essential" and therefore needful of safe working conditions in functioning buildings, the degree to which other workers and industries were viewed similarly appeared to depend on community-specific characteristics, such as the community's demographic and economic profile. Community leaders found themselves looking outward as well as inward, trying to determine "best practices" while keeping their own community's culture and needs at the forefront of their decision making. This lesson has direct implications for the work on functional recovery and community resilience. Both the FEMA-NIST report and NIST's Community Resilience Planning Guide can be leveraged to support the overarching idea that there are basic minimums—that is, agreement on the "essential" nature of some community functions and services—that should be considered as the starting point for achieving recovery-based objectives and established in codes, standards, or policies that communities may supplement or enhance as needed. Dialogue on the topic of "essential" functions and services needs to incorporate the voices of diverse community stakeholders, as historically underrepresented and vulnerable populations often bear a disproportionate share of disaster costs.

ACEHR calls upon the NEHRP agencies to implement the seven recommendations in the joint FEMA-NIST report and move the nation forward with respect to recovery-based objectives and community resilience. These efforts should include identification of the funding and research needed to support the recommendations in the joint FEMA-NIST report.

ACEHR acknowledges that both FEMA and NIST have continued partnering with ATC on the work of functional recovery and community resilience by adapting several existing work projects to incorporate a focus on functional recovery. This works aligns with the recommendations and proposed actions in the joint FEMA-NIST report and should help keep the nation moving forward on this key initiative. The ATC projects include:

- ATC-138 Project (FEMA-funded) – *Support of Performance-Based Seismic Design of Buildings* – Developing functional recovery methods and criteria for designing buildings to meet recovery-based objectives within the FEMA P-58 Methodology platform.

- ATC-150 Project (FEMA-funded) – *Improving the Nation's Lifelines Infrastructure to Achieve Seismic Resilience* – Reviewing the NIST CGR 14-917-33, Earthquake Resilient Lifelines: NEHRP Research, Development and Implementation Roadmap, and initiating selected activities related to lifelines resilience under Program Element I.

- ATC-152 Project (NIST-funded) – *Developing a Framework for Design of Lifeline Infrastructure Systems for Functional Recovery* – Preparing a NIST report that presents a framework to enable decision making for functional recovery of water, wastewater, and electric power lifeline systems after earthquake events.

While these projects address new buildings and lifeline infrastructure, the joint FEMA-NIST report also attaches significance to existing buildings and the social science mechanisms needed to enable a shift to functional recovery and community resilience. These projects represent a healthy start; more work is needed if the nation's citizens are to support and have confidence in the functional recovery of the built environment and lifeline infrastructure systems.

The topics of functional recovery and community resilience are of interest to agencies outside those in NEHRP. ACEHR considers it crucial that the NEHRP agencies collaborate effectively and efficiently within and between the various agencies on the topic of functional recovery and community resilience. This may require discovery of what different elements of the agencies are undertaking vis-à-vis these and related topics, including elements outside the usual NEHRP umbrella to include lessons from research on hazards other than earthquakes. Although different hazards may affect the built environment differently, what the public cares most deeply about is the disruption from normal routines caused by disasters. Casting a wide net to include historically underrepresented and vulnerable populations and gathering public comment on the recovery time for different types of buildings, services, industries, and lifeline infrastructure systems is an activity the NEHRP agencies could facilitate that would positively affect the further development of effective codes, regulations, and policies.

While intentional duplication of effort that enhances communication with key stakeholders (e.g., building owners) is valuable, unintentional duplication is not. Establishing and using consistent terminology in agency communications, along with co-sponsoring and coparticipating in the variety of webinars and public workshops being offered, are viewed by ACEHR as critical steps toward effective and efficient collaboration within and between agencies interested in functional recovery and community resilience.

ACEHR calls upon the NEHRP agencies to sponsor a multi-agency and multi-hazard workshop bringing together individuals, divisions, etc. working on functional recovery and community resilience and related topics. The purpose would be to exchange information and plan for facilitating intentional duplication and efficiencies.

Earthquake Early Warning Research

EEW systems detect Primary- (P-) wave energy from earthquakes, process this data algorithmically, and send alerts. Depending on the location of the epicenter and the speed of the system, alerts can reach people before the subsequent seismic shear (S) waves which bring the ground shaking that can cause earthquake damage. ShakeAlert on the U.S. West Coast is an EEW system, consisting of distributed seismometers (part of the Advanced National Seismic System) in California, Oregon, and Washington to detect shaking; data processing centers in California and Washington to detect and analyze earthquakes; and delivery systems to notify end users involving both public (e.g., the Wireless Emergency Alert (WEA) system, public universities, USGS) and private (e.g., Google) partners. Since the 2019 ACEHR report, USGS and partnering agencies have completed testing of public alerts to cell phones in northern California, Oregon, and Washington.

Benefit-cost analyses have shown that advanced warning of shaking from ShakeAlert is expected to trigger automated system responses and human protective behaviors the value of which exceeds the costs of building and maintaining the system. These responses include, for example, slowing high-speed trains, halting surgeries, switching industrial equipment into a safe state, and giving people a few seconds to drop, cover, and hold on. Increased situational awareness is also afforded by EEW and valued by end users. However, when the P- and S-wave arrivals are only seconds apart—as is typical of shallow crustal earthquakes in California—and the epicenter is in a population center, EEW may reach those end users after, concurrent with, or only a very few seconds before heavy shaking, limiting the potential benefits.

ShakeAlert and EEW development to date has focused on building out still incomplete networks of seismometers, improving data assimilation and algorithms, and developing and testing delivery platforms. Progress has been made on all these fronts, but challenges remain. Additional research on offshore ocean sensors and integration of Global Navigation Satellite System (GNSS) data could improve the value of the system, both for advancing scientific understanding of earthquakes as well as for protecting people and infrastructure. Early visions of the amount of information that could be sent in an alert had to be revised given the time and bandwidth limitations associated with the

WEA system, which is evolving but still constrained. While education and outreach efforts have increased markedly in the last few years, additional research is needed on how best to alert people in differing circumstances, including with differing warning times, varying physical response abilities (e.g., elderly, disabled), and in places with vulnerable infrastructure (e.g., unreinforced masonry). Additional research in earth science, engineering, and social science is needed to develop the system further and better understand how the system can best inform protective actions. Research on post-alert messaging and on how diverse users—such as schools, hospitals, and other places where people congregate, and organizations such as dam operators and refineries operating vulnerable infrastructure—do and can best use EEW is needed. To realize the full benefits of EEW, further investments in evidence-supported education and outreach campaigns are also needed, to increase awareness of EEW and to calibrate expectations of its performance.

ACEHR calls upon the NEHRP agencies to support research in earth science, engineering, and social science to further develop EEW capabilities and better understand how EEW can best inform protective actions. ACEHR also calls upon the NEHRP agencies to support investments in education and outreach campaigns to increase awareness and understanding of EEW.

BASIC RESEARCH TO SUPPORT NEHRP

Basic research in earth science, engineering, and social science is critical to the mission of NEHRP. Such research underpins efforts to understand and improve the seismic performance of the built environment, enhance the resilience of communities affected by earthquakes, and estimate future seismic hazards.

Among the NEHRP agencies, NSF's mission is most closely linked to basic research. ACEHR recognizes and strongly supports the exceptional track record of NSF in supporting NEHRP-relevant basic research through standing programs, research infrastructure, and special partnerships and competitions focused on "convergent" research. Programs in all fields at NSF can fund NEHRP-relevant research from solicited and unsolicited proposals. Besides intellectual merit, every proposal to NSF is reviewed for its broader impacts or societal contributions. Reducing vulnerability to earthquakes is recognized as an important broader impact. Special competitions, similarly, can fund NEHRP-relevant research deemed important. The convergent, cross-directorate Coastlines and People Competition (CoPe), for example, recently announced it will be funding a major research hub dedicated to Cascadia subduction zone hazards and mitigations, though earthquake hazards were not an explicit CoPe focus. ACEHR encourages continued focus on broader impacts as an important element of NSF merit review.

NIST and USGS also actively support and engage in basic research through initiatives such as the NIST-funded Center for Risk-Based Community Resilience Planning and USGS's internal and external research programs.

As noted previously, ACEHR applauds recent efforts to develop joint research programs among the NEHRP agencies, such as the DRRG and Civic Innovation Challenge programs. **ACEHR calls upon the NEHRP agencies to further undertake additional jointly funded activities depending on available resources and where synergy is applicable.**

As an example, the agencies might establish research programs using earthquake data to address practical needs in earthquake science, engineering, and public policy, including coordination on earthquake reconnaissance with multiple government, professional, and research or university organizations. The NEHRP agencies have effective mechanisms in place to undertake reconnaissance following extreme events, and to record and archive the data from such investigations. Reconnaissance research activities should take advantage of new technologies and protocols for data collection, archiving, and sharing developed for other hazards. The development of this infrastructure is a major accomplishment that places the U.S. in a global leadership position. One aspect that could be improved is pre-event planning and coordination between agencies and researchers outside the federal agencies, to ensure efficient and comprehensive recording of research datasets.

Following the collection of reconnaissance data, the current opportunities for data usage are relatively limited. NSF offers a Rapid Response Research (RAPID) funding mechanism to support follow-up research consistent with NSF priorities. NIST and USGS do not have dedicated programs for use of post-event reconnaissance data. This is a missed opportunity. Too often, current systems lead to a focused activity to collect data that is then underutilized. This can be addressed by establishing dedicated research programs to utilize earthquake data to enhance earthquake risk-reduction efforts.

RELATED TOPICS AND ISSUES

ACEHR has chosen to emphasize four related topics and issues—learning from the COVID-19 pandemic, multi-hazard approaches, climate change, and data-driven models and new sensing technology—that have significant potential to affect earthquake mitigation, preparedness, response, and recovery. Although these topics and issues are not directly related to earthquake science and engineering, there are aspects of each that highlight opportunities for the earthquake professional community to learn from and incorporate into earthquake risk-reduction efforts.

Learning from the COVID-19 Pandemic

Perhaps the most widespread disaster to strike the United States—and indeed, the world—in recent times is the global COVID-19 pandemic. The pandemic has affected every aspect of our lives. Some of the starker impacts of the pandemic have been the significant and disproportionately negative impacts on low-income populations, people of color, frontline workers, and small businesses, and their ability to effectively prepare and recover from the health and economic consequences of the pandemic.

The lessons learned in COVID-19 response and recovery provide important insights that should be further studied and applied to research and planning for earthquake preparedness and recovery, including the critical need for individual, family, and small business preparedness. The pandemic revealed the importance of people's primary residences, as they became *de facto* offices, schools, daycares, and other businesses—all dependent on building structures and lifeline infrastructure that remained functional. People were reminded that healthcare facilities and those who staff them play a crucial role in both disaster response and recovery. People were also reminded that community recovery after a disaster depends on open and functioning schools. The pandemic highlighted the negative effects of closed schools and daycares, including learning loss, loss of social interactions, loss of reliable nutrition, challenges for parents who could not return to work without adequate childcare, and employment stresses for school administrators, teachers, and staff. While people and organizations pivoted to remote work and virtual instruction, it was accomplished in an environment with none of the damage to buildings and lifelines that is expected from a significant earthquake.

The pandemic revealed the wide range of workers, businesses, and organizations considered essential for societal functioning, everything from healthcare to delivery services, along with whether those organizations had to have a bricks-and-mortar location—or not. The fragility of crucial supply chains was underscored by the short supply of many everyday supplies and the long-lasting impacts on product availability due to closures of manufacturing facilities and meat-processing plants, disruptions to transportation, and unavailability of workers. People were reminded that code officials—including building, fire, plumbing, mechanical, and electrical plan reviewers and inspectors and code enforcement officers—are essential to health and safety as they implement regulations that require disinfection of ventilation through mechanical systems in hospitals, adequate facilities to ensure handwashing, and safe and sanitary plumbing systems that mitigate the spread of contagions. They also ensure healthcare centers and schools are constructed and renovated safely. Code officials protect the health and welfare of building occupants by identifying dangerous or unsafe sanitary, air quality, structural, and electrical hazards. The pandemic demonstrated that maintaining code department operations is vital to response and recovery.

Researchers and policymakers should learn from and apply lessons on the impacts and successful interventions from the pandemic to earthquake preparedness, mitigation, and recovery planning and policy. As noted previously, those interested in functional recovery and community resilience should pay careful attention to what society considers essential and the conditions under which those elements of society need a bricks-and-mortar location along with supportive lifeline infrastructure. They should also observe how society adapted to physical distancing constraints by increasing many people's ability to work, shop, and learn from home while also relying on the continuing ability of some members of society to work outside the home, for example, healthcare workers and grocery employees. Finally, the need to maintain the functionality of residential structures and structures serving commercial and industrial purposes—along with critical lifeline infrastructure—has been a key lesson learned from this pandemic.

Multi-Hazard Approaches

Those who study earthquakes and their effects on the built environment, lifeline infrastructure systems, and socioeconomic systems have contributed significantly to research and policy conversations around earthquake mitigation, preparedness, response, and recovery. Much of what has been learned about earthquakes, their effects, and the means to mitigate and respond to them offer lessons applicable to other hazards. For example, the broad idea underlying performance-based design applies to buildings affected by wind as well as earthquakes. In the same vein, lessons learned from other hazards and resulting disasters may be considered and adapted by those in the earthquake field. One such opportunity is the National Landslide Preparedness Act enacted in January 2021.

NATIONAL LANDSLIDE PREPAREDNESS ACT

P.L. 116-323 directs the Secretary of the Interior, acting through the Director of the USGS, to establish a program to identify risks and hazards from landslides, reduce losses, protect communities at risk, and improve communication and emergency preparedness. The act requires the program to map and assess landslide hazards; respond to landslide events; coordinate with nonfederal entities to identify regional and local priorities; and develop and implement landslide hazard guidelines for geologists, engineers, emergency managers, and land-use decisionmakers.

ACEHR recognizes several potential synergies with planning for parallel or sequential hazards that occur within the same response and recovery period as an earthquake (e.g., landslides, liquefaction, fires) as well as planning for distinct hazards (e.g., wildfires, floods, hurricanes, tornados). Parallel or sequential hazards occurring within the same response and recovery period may complicate or impact earthquake response efforts; understanding their specific nature along with their likely effects on buildings and lifelines is essential to effective response. Communication challenges, sheltering needs, evacuation planning, supply chain impacts, and more tend to follow the same paths regardless of the nature of the disaster. Importantly, communities are interested in resuming life as normally as possible as quickly as possible regardless of the nature of the disaster, hence the need for delineating recovery-based objectives as they relate to the built environment and lifeline infrastructure systems.

With respect to existing buildings and lifeline infrastructure systems, it is well understood in the earthquake mitigation community that most older buildings and lifelines require seismic retrofits or replacement to protect occupants and survive earthquakes. These same buildings and lifelines may also need retrofits to address floods, wildfire, and/or hurricane hazards. Sustainability goals are also driving owners of older buildings and lifelines to think about weatherization and energy upgrades. Holistic and integrated strategies are needed to address the range of retrofits that may be required of older buildings and lifelines while maintaining affordability and preventing displacement of low-income and vulnerable populations. Seismic retrofits should be considered as part of a suite of upgrades competing for limited funding and financing. Rehabilitating or retrofitting historical buildings provides an additional layer of complexity.

New construction and retrofits/upgrades of buildings are guided by current building codes and standards. Those documents may be considered somewhat holistic in that all structural hazards (e.g., seismic, wind, tornado, snow, flood) are considered within one document. However, for an improved holistic approach, each individual hazard-resistant structural design should consider the results and benefits of the other hazard-resistant designs, and benefit from that synergy. An example is a recent consideration and development of a performance-based design approach for wind that is compatible with current earthquake performance-based design methods. Coordination of blast design with seismic detailing is another example. This approach may achieve even further synergy when considering the more resilient performance objectives (i.e., those above life safety). Balancing and blending the goals of sustainable design (which might call for the use of less material) with recovery-based hazard-resistant design (which might call for additional redundancy and/or strength to minimize damage and downtime) would contribute to a more holistic and integrative design approach. Further benefits may be achieved when design approaches are also coordinated with non-structural issues such as energy conservation, infrastructure, wildfire, response, city planning, and other social issues. Better communication and coordination are needed within the structural hazard groups (e.g., seismic, wind, tornado, snow), as well as among the non-structural concerns of energy, infrastructure, sustainability, and social-equity issues to achieve recovery-based objectives and community resilience.

Climate Change

Research on climate change suggests it may already be affecting the nation with respect to earthquakes. Several issues demand further research and action, including multi-hazard issues; induced seismicity from fluid injection, geothermal energy, and carbon sequestration; effects of groundwater change on seismic hazard; and the potential impacts of mitigating climate change, including negative unintended consequences.

Many multi-hazard issues affecting earthquake mitigation, preparedness, response, and recovery may be linked to climate change. Researchers have noted that climate change has the potential to modulate earthquake-induced chains of geologic hazards and exacerbate their extent, magnitude, and damages. For example, sea level rise, changes in precipitation patterns, ground water levels, and storm surge—resulting from climate change—are likely to increase co-seismic tsunami and liquefaction hazards. Sea level rise could impact tsunami inundation zones and increase the impact of post-event subsidence, putting more people at risk, requiring additional inundation mapping, and modifying safe escape guidance for at risk communities. Depending on how rapidly and extensively sea level rise happens, millions of people may lose coastal land and be displaced, which increases demand on development in high-risk (dry land) areas. This will also require some infrastructure to be moved/elevated/reinforced (e.g., roads, bridges, utilities) and repaired more often due to increased frequency and severity of damage from incidents.

Climate change may also affect immediate and downstream risks from co-seismic landslides, both directly through soil conditions and indirectly through effects on vegetation, flooding, infrastructure, and adaptive capacity, vulnerability, or resilience. Locations with more intense rain events or prolonged rainy seasons could see an increase in saturated soils leading to greater liquefaction and landslide risk during an earthquake. There may also be implications for existing liquefaction and landslide maps.

Additionally, impacts of climate change could exacerbate fires and secondary effects of seismic events. We are seeing dangerous increases in fire activity and behavior due to climate change. At the same time, we are seeing massive encroachment into the wildland-urban interface. During the dry season, fires resulting from earthquake damage could significantly impact response and recovery operations. Also, depending on the severity of the earthquake damages, firefighting resources may not be available.

In addition to multi-hazard issues, we note the potential for induced seismicity from fluid injection for gas and oil extraction, increased reliance upon geothermal energy, and carbon sequestration. At present, the U.S. leads the world in geothermal electricity generation. In 2020, there were geothermal power plants in seven states, which produced about 17 billion kWh, equal to 0.4% of total U.S. utility-scale electricity generation. Most geothermal power plants in the U.S. are in western states and Hawaii, where geothermal energy resources are close to the earth's surface. The Geysers dry-steam reservoir in northern California is the largest known dry-steam field in the world and has been producing electricity since 1960.

In 2021, President Biden set a target for the U.S. to achieve a 50-52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution by 2030. Expanding geothermal energy may be key to meeting the country's climate goals and geothermal electricity generation has the potential to significantly increase in capacity in the coming decades. Most geothermal power plants inject the geothermal steam and water that they use back into the earth. This has been demonstrated to cause induced seismicity and therefore is relevant to those focused on earthquake mitigation, preparedness, response, and recovery. Further research is needed to better characterize and develop efforts to successfully forecast induced seismicity in geothermal fields.

The United States' climate goals may in part be reached by capturing and sequestering carbon from point sources underground in depleted oil and gas reservoirs, saline formations, or deep, unmineable coal beds. The research agenda published by the National Academies of Science, Engineering, and Medicine calls for roughly $1 billion to advance the deployment of carbon sequestration in deep sedimentary reservoirs at large scale over 10–20 years. A challenge to the ambitions of carbon sequestration is the potential for induced seismicity that can cause earthquakes in locations that have not previously experienced them. Once again, further research is needed to understand the potential for such earthquakes and how to mitigate their impacts.

Groundwater changes resulting from climate change may also affect seismicity. Seismicity changes are known to occur due to changes in groundwater extraction or recharge. Further, sea level rise and seawater intrusion in coastal areas will affect coastal groundwater levels and liquefaction susceptibility. In addition to seismicity changes, changing groundwater levels and their consequences may contribute to reductions in the performance and lifespan of buildings.

Not yet known is how efforts to mitigate climate change will affect earthquake risk relative to the built environment and lifeline infrastructure systems. Changes to power, gas, and other utility distribution systems seem likely as governments adopt laws and codes to reduce or phase out reliance on fossil fuels. Changes in land use (e.g., retreating from coastal areas) could also affect tsunami risk. Relocation and retreat from flood-prone areas are receiving increased attention as sea levels rise. Finally, battery and energy storage technologies are being adopted that integrate solar power into the grid and help make power grids and individual buildings more resilient to seismic risks.

Data-driven Models and New Sensing Technologies

LiDAR, Interferometric Synthetic Aperture Radar (InSAR), nodal seismic, and Distributed Acoustic Sensing (DAS) are examples of rapidly developing technologies that can gather terabytes of data per day. Each of these sensing technologies present research opportunities that will require new analytic approaches. Data management and distribution will have to adapt. On the software side, data-intensive computing approaches, such as machine learning, will need to be developed to take full advantage of these opportunities. On the hardware side, graphics processing unit (GPU), edge, and cloud computing may all play important roles. It will be challenging to adapt to this shifting sensing and computing landscape, but the payoff could be immense for earthquake mitigation, preparedness, response, and recovery.

Open-science principles, including open-source code, open data, and open access to publications are trends that could accelerate progress and broaden and deepen impact in earthquake science and engineering. These principles are particularly important for early career scientists and have become the norm in, for example, research computing. They enable collaborative work, building on best practices, but come with many challenges—such as how to fund, archive, and peer review research publications—that need to be addressed.

ACEHR calls upon the NEHRP agencies to help organize workshop(s) for the earthquake science and engineering community to explore how applying lessons learned from the COVID-19 pandemic, multi-hazard approaches, climate change, and data-driven models and new sensing technologies can enhance earthquake risk-reduction efforts. The purpose of such workshops would be to identify lessons from these evolving topics and issues that may enhance multidisciplinary thinking and approaches to earthquake risk reduction.

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