OPINION

NEHRP Turns 40

This year, the National Earthquake Hazards Reduction Program (NEHRP) turns 40, four decades since the Earthquake Hazards Reduction Act of 1977 was enacted establishing the Program, spurring numerous federal, state, and community actions to reduce earthquake losses in the U.S.A. and its territories and setting a standard for earthquake loss-reduction projects internationally. Four agencies are partners in NEHRP: the Federal Emergency Management Agency (FEMA), the National Institute of Standards and Technology (NIST, the lead agency), the National Science Foundation (NSF), and the U.S. Geological Survey (USGS).

The genesis of NEHRP has been well covered in previous summaries by Wallace (1996) and Hamilton (2003), each of whom described the earthquakes, the people, and the reports that led to the passage of the 1977 Act. The 1964 Alaska and 1971 San Fernando earthquakes were, of course, seminal events. Several expert panels weighed in, there was great enthusiasm for earthquake prediction, and even the ephemeral Palmdale Bulge contributed. There is no need to repeat those good stories here; instead, I will review what has been accomplished since the Act was passed and what key objectives are yet to be realized. In this space, it will not be possible to cover this topic comprehensively, so indulge me while I survey just a few highlights.

Remarkably few major earthquakes have occurred since 1977, in terms of economic impact, so the earthquake threat has faded from the memories of most Americans, even as geologists and seismologists have identified and quantified a number of fault systems that pose risks of national economic scale.

First, remarkably few major U.S. earthquakes have occurred since 1977, at least in terms of economic impact. In fact, only three have caused losses greater than $1 billion: 1989 Loma Prieta, $10.7 billion; 1994 Northridge, $64.0 billion; and 2001 Nisqually, $2.7 billion (Wilkerson, 2016). Yet, FEMA (2008) estimated annualized earthquake losses in the U.S.A. at $5.3 billion, based on long-term earthquake patterns and ever-growing economic exposure in the built environment (revised to $6.1 billion in FEMA, 2017, Publ. 366). Assuming, and believing, that those estimates are based on good data and sound earthquake science suggests that we have been lucky. But a consequence of this good fortune is that the earthquake threat to the nation has faded from the memories of most Americans, even as geologists and seismologists have identified and quantified a number of fault systems that pose risks of national economic scale. Examples are the southern San Andreas and Hayward faults in California, the Cascadia subduction zone in the Pacific Northwest, the New Madrid Seismic Zone of the central U.S.A., and segments of the Alaska-Aleutian subduction zone. Notably, all five of these high-hazard areas have been played by FEMA in recent years in national-level disaster response exercises.

KEY ACCOMPLISHMENTS

Although we have suffered only a few major earthquake disasters, many significant achievements since 1977 have already led to earthquake loss reduction nationally and internationally and will lessen losses in future large U.S. earthquakes. First, we now enjoy much faster and more accurate characterizations of earthquakes (e.g., Hayes *et al.*, 2011), distributed through rapid, actionable situational-awareness products from the USGS, such as ShakeMap, ShakeCast, "Did You Feel It?," and PAGER, as well as faster and more robust tsunami warnings from the National Oceanic and Atmospheric Administration (NOAA) Tsunami Warning Centers. This capability has been enabled, first, by the completion of the Global Seismographic Network (GSN; Butler *et al.*, 2004), including, by 2011, real-time broadband coverage. Second, both the USGS National Earthquake Information Center and NOAA Tsunami Warning Centers now operate continuously, with 24 × 7 staffing. Third, over the past 25 years, the USGS has worked with regional seismic network operators, in most cases in academic institutions, to stabilize funding for routine operations, to modernize equipment, and to standardize analysis techniques and reporting protocols. By 1999, this effort led to the formation of the Advanced National Seismic System (ANSS; see Filson and Arabasz, 2017), which was authorized in 2000 by NEHRP legislation (Public Law 106-503). With a push from the academic community and support from the NSF, the USGS completed a 100-station ANSS National Seismic Network in 2006. More recently, NSF and USGS have worked together to incorporate temporary seismic stations established for the NSF research project EarthScope into permanent stations of the ANSS. However, even though it now comprises nearly 3000 modern seismic stations, ANSS remains only about 40% completed relative to its design (see USGS Circular

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1188, 1999). Another major achievement of the collaboration between USGS, NSF, and the academic community is that all current and past data from the ANSS, GSN, and U.S. regional networks, along with data from many international contributors, are openly available through the Data Management Center of Incorporated Research Institutions for Seismology, which now serves as an invaluable resource for studies of earthquake sources and ground motions that underlie much of NEHRP research.

Much of modern construction in the U.S.A. is now earthquake resistant. When NEHRP was established, the seismic safety elements in model building codes were based on a simple national-scale map, available in hard copy only, which categorized expected ground shaking severity in six broad zones. This means of conveying ground shaking hazard was very crude and difficult to use; in some cases the boundaries between zones passed through major cities, in others they followed state lines. Today seismic hazard in the U.S.A. is based on a national model of expected ground shaking derived from a probabilistic seismic-hazard analysis conducted by the USGS. This National Seismic Hazard Model (NSHM) combines available and credible data on historical seismicity, recently active geologic faults, geodetic data, and the characteristics of seismic-wave propagation nationwide and provides expected levels of ground shaking at any point in the country, based on user-specified probability and exposure time constraints. The procedures and assumptions used in making this model are transparent and publically available. The NSHM is reviewed and updated every six years to take into account the results of new data, investigations and research. The NSHM was also recently extended to include the effects of induced seismicity in the central and eastern U.S.A. (in parts of which recent seismicity has exceeded that of California), including a 1-year ground-motion hazard forecast (Petersen *et al.*, 2016).

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Another major accomplishment due to NEHRP is the collaboration between FEMA, NIST, and USGS in developing model building codes. FEMA and USGS work together to use the results of the NSHM to develop seismic design maps, with the Building Seismic Safety Council and the American Society of Civil Engineers, cast in terms readily understood and useable by engineers. FEMA and NIST work with these organizations to translate research in seismic design into proposed provisions for the many other seismic safety elements of model building codes. These developments are, in turn, submitted to the International Code Council to aid in specifying a model International Building Code (IBC). The IBC is used in the design and construction of earthquake-resistant buildings and other structures.

The adoption and enforcement of building code provisions is the responsibility of states and municipalities, not dictated by federal regulation. However, as can be inferred from the process described above, development of a seismic building code is a complicated process, often beyond the expertise and resources of a single state or city. The IBC model provides a credible and comprehensive reference that jurisdictions often adapt entirely or in part to include in their building-safety statutes.

NSF has taken the lead for NEHRP in supporting engineering research studies to improve the performance of structures during earthquakes. Because lateral seismic forces on structures during an earthquake can be a significant fraction of the weight of the structure itself, special design and construction criteria must be developed and used to resist these forces. NSF has supported not only individual studies to address these problems but also the consortia that develop engineering R&D facilities to test proposed solutions, including using full-scale models. For its part, the USGS and its partners, including the California Geological Survey and the Veterans Administration, installed seismic instruments in hundreds of buildings in earthquake-prone areas and, with other partners, jointly deliver strong ground motion recordings through the Center for Engineering Strong Motion Data.

Under NEHRP, FEMA developed Hazards U.S. (HAZUS), a nationally applicable standardized methodology that contains models for estimating potential and actual losses from earthquakes, floods, and hurricanes. HAZUS uses Geographic Information Systems technology to estimate the physical, economic, and social impacts of disasters. The USGS earthquake-hazard assessment tools and quantification of impacts described above provide the components needed to create realistic earthquake shaking scenarios for use with HAZUS. These scenarios and related impact assessments are critical when local governments need to apply for funds for earthquake mitigation purposes. They also provide realistic situations for emergency response planning and training exercises and are consequently heavily used.

New national-scale assessments of earthquake risk, both for annualized earthquake losses and population exposure to strong ground shaking, have updated and technically refined earlier estimates. These assessments indicate that nearly half of Americans now live in areas prone to, in the long term, earthquake damage. In high-hazard urban areas such as Los Angeles, a result of better hazard and risk quantification has been new policy and regulatory action. In December 2014, Los Angeles Mayor Eric Garcetti released a major plan, Resilience by Design (2015), to strengthen buildings, fortify the water system, and ensure reliable telecommunications. This plan was developed by a Seismic Safety Task Force using the results of the ShakeOut Scenario (Jones *et al.*, 2008). The Seismic Safety Task Force was able to apply NEHRP-funded seismic and engineering results to make specific recommendations to retrofit for seismic safety and improve the disaster resilience of Los Angeles urban systems. A comparable study has also been completed for San Francisco (Resilient San Francisco, 2016).

Other significant NEHRP accomplishments, too numerous to cover in detail here, improved understanding of earthquake source processes, fault system modeling, probabilistic earthquake forecasting, and the causes of induced seismicity. NEHRP also led to several major advances in geodetic monitoring, imaging, and modeling at all scales, leading to improved models of fault loading, coseismic and postseismic fault slip, and tsunami generation.

PAST AND CURRENT CHALLENGES

There have also been a few significant disappointments. The greatest of these is probably the unfulfilled promise of earthquake prediction. To quote the National Earthquake Prediction Evaluation Council (NEPEC) (2016): "Despite widespread optimism in the 1970s and 1980s, reliable short-term (over days to a year) prediction of large earthquakes has proven an elusive goal… decades of rigorous research have failed to produce a reliable short-term prediction method. This lack of progress has led many researchers to conclude that short-term prediction may be impossible." Yet the research that has been accomplished while seeking to predict earthquakes, such as from the Parkfield Prediction Experiment (Roeloffs and Langbein, 1994; Bakun *et al.*, 2005), has led to extremely valuable knowledge of the earthquake process and its variability in space and time, insights that have led to significant advances in probabilistic earthquake forecasting in recent years.

For the current lack of NEHRP program authorization that has prevailed since 2009, the most obvious impact is the lack of visibility for the four-agency program within Congress; earthquakes still seem to be largely thought of as a "West Coast thing."

NEHRP has also had significant budget challenges. These include not only an overall budget that has not kept up with inflation but also large cuts to FEMA funding in 1999, 2001, and 2003 (FEMA funding in 2016 was about half of its late 1990s peak) and an overall budget reduction, so-called budget "sequestration," at all four NEHRP agencies in 2013. Whether as a result of funding cuts or deprioritization by a NEHRP agency, NEHRP funding ended for such activities as the Network for Earthquake Engineering Simulation (an NEHRP facility established by legislation), the American Lifelines Alliance, and several of the ANSS regional seismic networks. Funding was also significantly reduced for the *Learning From Earthquakes* activity that facilitates postearthquake reconnaissance.

Since the original legislation passed in 1977, NEHRP has been reauthorized 11 times, with periods of authorization lasting from one to five years. The last reauthorization legislation was passed in 2004, covering the period 2005–2009. For the current lapse of program authorization that has prevailed since 2009, the most obvious impact is the lack of visibility for the four-agency program within Congress; earthquakes still seem to be largely thought of as a "West Coast thing." This may be largely caused by the blessing of having no earthquake disaster with a national-scale impact since the 1994 Northridge earthquake. To its credit, Congress has held a number of NEHRP hearings since 2009, but these have not resulted in a program reauthorization being passed.

One should ask, considering resource and visibility challenges of the past 40 years, is the U.S.A. "behind" other countries, such as Japan or Chile, in a loss-reduction sense? When the magnitude 9.0 Tohoku-oki earthquake hit northern Honshu in March 2011, losses from strong ground shaking were relatively small (not so for the tsunami, of course, and total damage from the earthquake and tsunami is estimated at \$232 billion); the same was true in the **M** 8.8 earthquake that struck Chile in 2010. When a similar-size earthquake strikes Cascadia, will the U.S.A. fare so well? Probably not, for the Cascadia Rising national response exercise, conducted last year by FEMA and three west-coast states (California, Oregon, Washington), the consequences of an **M** 9 earthquake on the subduction zone in 2016 were estimated at more than 10,000 dead, more than 30,000 injured, and \$81 billion or more in direct losses (FEMA *et al.*, 2015; see also Cascadia Regional Earthquake Working Group [CREW], 2013). Adding indirect losses from business interruption, this will be an event of national significance, and likely global economic consequences, given that the annual GDP of the affected region is currently close to \$1 trillion.

LOOKING FORWARD

There are several opportunities, both in the near term and long term, for reducing future earthquake and tsunami losses in the U.S.A. The federal advisory committee for NEHRP, the Advisory Committee for Earthquake Hazard Reduction (ACEHR; annual reports online at nehrp.gov), and the National Research Council (NRC, 2011) have both weighed in with specific recommended actions. The NRC envisaged and detailed 18 distinct areas of fruitful future loss-reduction work, ranging from ANSS completion to performance-based engineering, to social science response and recovery research. Recent-year recommendations by the ACEHR have primarily been on program management and budget issues, but they also called for: (1) expanding earthquake scenario development in conjunction with stakeholder engagement to examine consequences of earthquakes in high-risk urban areas; (2) conducting research and development on critical infrastructure and lifeline systems, geotechnical engineering, nonstructural elements, and residential and industrial structures that have seismic vulnerabilities; and (3) enhancing investment in social-science research related to earthquake hazards and disasters.

Most recently, an emerging priority has been improving the earthquake resilience of the nation's critical infrastructure. This includes constructing critical facilities to obtain performance beyond "life-safety" (i.e., not to collapse or otherwise permanently fail), providing rapid situational awareness to the operators of this infrastructure (e.g., airports, pipelines, the power grid), and providing advance warning of strong ground shaking so that protective actions can be taken via earthquake early warning, which is now being implemented by the USGS and its partners for the U.S. West Coast. The tsunami-triggered meltdown of the Fukushima, Japan, nuclear reactors in 2011 is a strong impetus for critical facilities to invest in protecting these systems that are vital for our health and safety. The 2011 Virginia **M** 5.8 earthquake that produced ground motions at the North Anna nuclear power plant that exceeded its design criteria, and the occurrence of recent damaging earthquakes in the Cushing, Oklahoma, the location of a major oil storage facility and pipeline crossroads, bring these concerns home.

Further reducing earthquake losses in America is quite feasible but will take a concerted effort by the NEHRP agencies and the scientists and engineers that support them. Opportunities abound; for example, uncertainty in earthquake ground motions in the central and eastern U.S.A. is simply too high for confident decision making. Uncertainties in great earthquake recurrence rates in southern Cascadia are currently about a factor of 2, also obviously too high for many loss-reduction purposes and weakening state and local efforts to raise awareness of the threat. We also have a very realizable opportunity to improve the reliability of earthquake forecasting (Jordan *et al.*, 2014), which should allow earthquake insurance and reinsurance premiums to be more confidently set, potentially lowering earthquake insurance costs, among other benefits (Field *et al.*, 2016).

> **Will this scientific and engineering work be cost effective? Despite the recent lull in domestic seismic activity, there will of course be future damaging earthquakes in the U.S.A., so the answer is yes.**

In terms of improved earthquake and tsunami monitoring, quantification, and reporting, there is also tremendous promise in real-time Global Navigation Satellite Systems positioning and geodetic imaging, technologies that were barely on the horizon when NEHRP began and certainly not a part of the earthquake-observing toolkit. Collectively, geodetic observations have unique capabilities for recording displacements of millimeters to meters, over distances of meters to thousands of kilometers, and for recording time spans of seconds to decades, in 3D and, increasingly, in real time. Extraordinary images obtained from Light Detection and Ranging and Interferometric Synthetic Aperture Radar mapping of faults have enabled new insights into the slip distribution during and after recent earthquakes that are not possible with any other approach. Imminent improvements facilitated by these and other geodetic and remote-sensing technologies include more accurate earthquake-hazard models, tsunami warnings, earthquake early warnings and earthquake forecasts. Offshore, seafloor geodesy may be used for inferring interseismic strain accumulation and for rapidly quantifying megathrust earthquake slip. Loss reduction applications of these new technologies will blossom in the next few years.

Will all this scientific and engineering work be cost effective? Despite the recent lull in domestic seismic activity, there will of course be future damaging earthquakes in the U.S.A., so the answer is yes. In 2005, the NRC looked at the costs and benefits of completing the ANSS and concluded that the benefits were ~10 times the costs (NRC, 2006). Just in terms of benefits to performance-based engineering, that study estimated benefits of $280 million per year (2004 dollars) versus an ANSS operating cost of about $42 million per year. Because the cost of collecting quality data on earthquakes and issuing rapid, accurate situational-awareness products is only a fraction of the four-agency NEHRP budget, these estimates show that we are in a much better than break-even situation.

Finally, Congress created NEHRP as a national and interagency program, importantly recognizing that earthquakes are not strictly a "West Coast problem" or limited to the purview of only one sector of the federal government. Today, when we assess that nearly 150 million Americans are exposed to potentially damaging ground shaking (Jaiswal *et al.*, 2015), we should strive to see that NEHRP reaches its full potential as an active federal program in which loss-reduction goals and agency roles are well defined, oversight and coordination is well established, and there is no overlap of responsibilities or competition for turf or funding. NEHRP must continue to work with state and local governments and professional groups to define earthquake hazards and effective loss-reduction measures, and the NEHRP agencies must engage internationally to integrate the lessons learned from earthquake disasters abroad into domestic loss-reduction activities. NEHRP is a federal program that after 40 years has the potential to continue to serve the nation well. Striving for the highest level of earthquake science and its application to loss reduction and continuing to make the case for its importance to local, regional, and national officials, deserves the continued engagement of the entire seismological and earthquake-engineering community.

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