U.S. Geological Survey Earthquake Hazards Program Decadal Science Strategy, 2024–33

Circular 1544

U.S. Department of the Interior
U.S. Geological Survey

Covers: Photograph showing U.S. Geological Survey research geologist preparing to measure the offset of a crevasse on the Canwell Glacier, taken November 2002. Photograph by U.S. Geological Survey, continued on back cover.

This page: Student intern helping with the installation of a new seismometer at Intermountain West seismic station SNOW (Snow Kind Mountain, Wyoming), August 5, 2016. Photograph by Steven Ploetz, U.S. Geological Survey.

Background: Image courtesy of prapann—https://stock.adobe.com/

U.S. Geological Survey Earthquake Hazards Program Decadal Science Strategy, 2024–33

By Gavin P. Hayes, Annemarie S. Baltay Sundstrom, William D. Barnhart, Michael L. Blanpied, Lindsay A. Davis, Paul S. Earle, Ned Field, Jill M. Franks, Douglas D. Given, Ryan D. Gold, Christine A. Goulet, Michelle M. Guy, Jeanne L. Hardebeck, Nico Luco, Frederick Pollitz, Adam T. Ringler, Katherine M. Scharer, Steven Sobieszczyk, Valerie I. Thomas, and Cecily J. Wolfe

Circular 1544

U.S. Department of the Interior
U.S. Geological Survey

U.S. Geological Survey, Reston, Virginia: 2024

Suggested citation:
Hayes, G.P., Baltay Sundstrom, A.S., Barnhart, W.D., Blanpied, M.L., Davis, L.A., Earle, P.S., Field, N., Franks, J.M., Given, D.D., Gold, R.D., Goulet, C.A., Guy, M.M., Hardebeck, J.L., Luco, N., Pollitz, F., Ringler, A.T., Scharer, K.M., Sobieszczyk, S., Thomas, V.I., and Wolfe, C.J., 2024, U.S. Geological Survey Earthquake Hazards Program decadal science strategy, 2024–33: U.S. Geological Survey Circular 1544, 55 p., https://doi.org/10.3133/cir1544.

ISSN 2330-5703 (online)

U.S. Geological Survey geologists make measurements of fault rupture from the 2019 magnitude 7.1 Ridgecrest, California, earthquake. Photograph by Ben Brooks, U.S. Geological Survey.

Acknowledgments

The Earthquake Hazards Program (EHP) is grateful for reviews from Michael Hamburger, Kevin Furlong, and members of EHP external advisory committees, including the Scientific Earthquake Studies Advisory Committee, the Advanced National Seismic System Steering Committee, the Earthquake Early Warning External Working Group, and the National Seismic Hazard Model Project Steering Committee. The EHP also received feedback from the Advanced National Seismic System National Implementation Committee. All of these various contributions helped to improve this Circular.

From the U.S. Geological Survey, the EHP also thanks Jonathan Godt, Sara McBride, Ben Brooks, Harley Benz, and David Wald for their contributions.

U.S. Geological Survey seismologist and research geophysicist conduct field work near the main rupture between Trona and Ridgecrest after the July 2019 magnitude 7.1 Ridgecrest, California, earthquake. Photograph by Nicholas van der Elst, U.S. Geological Survey.

Contents

Figures

Table

Supplemental Information

Throughout the text, two types of priorities, shown in bold text, are described: foundational and aspirational.

U.S. Geological Survey field engineers working on the borehole at Global Seismographic Network Station HRV at the Adam Dziewonski Observatory in Oak Ridge, Massachusetts, July 27, 2023. Photograph by Ambrose McCabe, U.S. Geological Survey.

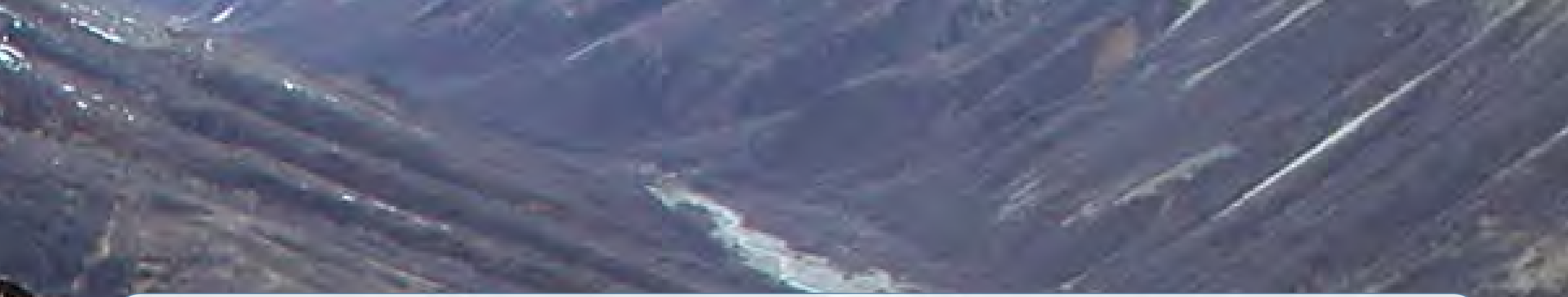
Abbreviations

ANSS	Advanced National Seismic System
ANSS-SC	Advanced National Seismic System Steering Committee
BHA	Bureau for Humanitarian Assistance
DAS	distributed acoustic sensing
DEIA	diversity, equity, inclusion, and accessibility
DOI	Department of the Interior
EDAT	Earthquake Disaster Assistance Team
EEW	earthquake early warning
EEWEWG	earthquake early warning external working group
EHP	Earthquake Hazards Program
EHPC	Earthquake Hazards Program Council
EHPO	Earthquake Hazards Program office
ERF	earthquake rupture forecasting
ESC	Earthquake Science Center
ESP	earthquake source processes
FEMA	Federal Emergency Management Agency
FY	fiscal year
GHSC	Geologic Hazards Science Center
GMM	ground-motion model
GNSS	global navigation satellite system
GSN	Global Seismographic Network
HIR	hazard, impacts, and risk
IPT	integrated products team
IT	information technology
MCC	management coordination committee
NEHRP	National Earthquake Hazards Reduction Program
NEIC	National Earthquake Information Center
NEPEC	National Earthquake Prediction Evaluation Council
NHMA	Natural Hazards Mission Area
NIC	National Implementation Committee
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NSHM	National Seismic Hazard Model
NSHMP-SC	National Seismic Hazard Model Project Steering Committee
NSMP	National Strong Motion Project

OAF	operational aftershock forecasting
OCAP	Office of Communications and Publishing
OEF	operational earthquake forecasting
PAGER	Prompt Assessment of Global Earthquakes for Response
Risk COP	Risk Research and Applications Community of Practice
RSN	regional seismic network
SESAC	Scientific Earthquake Studies Advisory Committee
SCC	science coordination committee
SCEC	Statewide California Earthquake Center
SZS	subduction zone science
TWC	Tsunami Warning Center
USGS	U.S. Geological Survey

Helicopters and satellite phones were integral to the geologic field response to the November 2002 magnitude 7.9 Denali, Alaska, earthquake. Here, a research geologist is calling a seismologist to pass along the discovery of the Susitna Glacier thrust fault. The view is to the north up the Susitna Glacier. The Denali fault trace lies in the background where the two landslides can be seen. Photograph by Peter Haeussler, U.S. Geological Survey.

Geologists inspect a 5-meter fault offset near Delta River, Alaska, caused by the 2002 magnitude 7.9 Denali earthquake. Photograph by Peter Haeussler, U.S. Geological Survey, continued on next page.



U.S. Geological Survey Earthquake Hazards Program Decadal Science Strategy, 2024–33

By Gavin P. Hayes, Annemarie S. Baltay Sundstrom, William D. Barnhart, Michael L. Blanpied, Lindsay A. Davis, Paul S. Earle, Ned Field, Jill M. Franks, Douglas D. Given, Ryan D. Gold, Christine A. Goulet, Michelle M. Guy, Jeanne L. Hardebeck, Nico Luco, Frederick Pollitz, Adam T. Ringler, Katherine M. Scharer, Steven Sobieszczyk, Valerie I. Thomas, and Cecily J. Wolfe

Executive Summary

Earthquakes represent one of our Nation's most significant and costly natural hazards, with estimated annual loses from earthquakes close to $15 billion in 2023. Over the past two centuries, 37 U.S. States have experienced an earthquake exceeding a magnitude of 5, and 50 percent of States have a significant potential for future damaging shaking; these statistics speak to the need for nationwide interest and investment in earthquake hazard characterization and risk reduction.

Authorized under the Earthquake Hazards Reduction Authorization Act, the U.S. Geological Survey (USGS) Earthquake Hazards Program (EHP) provides the scientific information, situational awareness, and knowledge necessary to reduce deaths, injuries, and economic losses from earthquakes and earthquake-induced tsunamis, landslides, and soil liquefaction. The EHP supports activities in three focused topical areas: (1) earthquake monitoring, (2) hazard assessment, and (3) applied research, using the results of each—and the coordination among them—to further support risk translation and communication in regions at risk nationwide.

For earthquake monitoring, the Advanced National Seismic System (ANSS), a cooperative effort of USGS networks, university partner regional seismic networks, and real-time geodetic networks, collects and analyzes data on earthquakes; issues timely, reliable notifications of their occurrence and impacts; and provides data for earthquake research, hazard, and risk assessment as a foundation for building an earthquake-resilient Nation. The USGS-operated ShakeAlert Earthquake Early Warning system is a recent addition to EHP's ANSS infrastructure.

In the realm of earthquake hazard assessment, the EHP contributes to earthquake risk mitigation strategies by developing the National Seismic Hazard Model and maps, and other related products, that describe the likelihood and potential effects of earthquakes nationwide, especially in the urban areas of highest risk. The EHP also conducts research on the causes, characteristics, and effects of earthquakes and prioritizes work that directly increases the accuracy and precision of earthquake hazards assessments, earthquake forecasts, and earthquake monitoring and situational-awareness products and that supports the Nation's earthquake mitigation practices.

Bridging the EHP's efforts across research, hazard assessments, and earthquake monitoring is a broad and comprehensive collection of earthquake information products, including the National Seismic Hazard Model, ShakeAlert, and other products describing impact, such as ShakeMap and PAGER (Prompt Assessment of Global Earthquakes for Response), which have been developed and integrated into EHP's real-time monitoring systems.

EHP funds external partners to carry out many important collaborative activities through an active external grants program—one of the largest in the USGS—and through cooperative agreements with other partners such as the university-operated regional seismic networks, funded as part of the ANSS.

To continue its support of earthquake hazard characterization and risk reduction, the EHP aims to strengthen its foundational products and practices while positioning itself to respond to the evolving needs of the Nation and follow best practices of the scientific community. This document describes a strategy for the program to ensure it can meet these demands. The foundational priorities outlined in this strategy represent those activities that remain critical to the core functionality of the program and those that can be supported under current fiscal year 2024-level appropriations. Priorities described as aspirational are important for future growth, and to maintain the program's position as a leading global resource in earthquake science, but would require increases in appropriated funding to be fully realized.

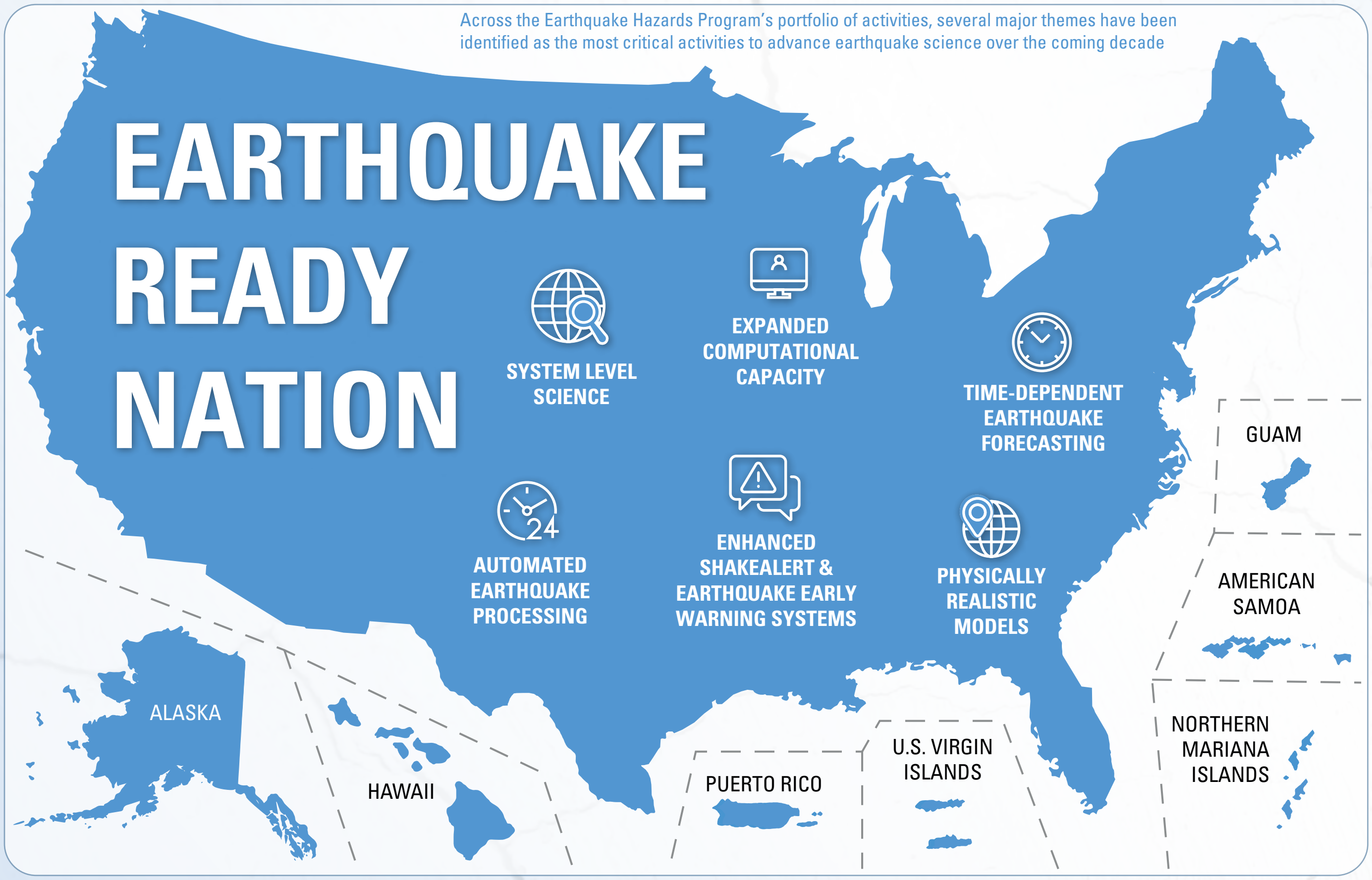


Figure ES1. Priorities of the Earthquake Hazards Program that promote an earthquake-ready Nation (icons courtesy of Cherry, Julien Eichinger, and kolonko—https://stock.adobe.com/).

Across the program's portfolio of activities, several major themes, which are highlighted in figure ES1, have been identified as the most critical activities to advance EHP science over the coming decade. Together, these activities provide the framework necessary to integrate critical hazard characterization and risk reduction activities across the program. They provide the structure for research to advance the understanding of where, when, and why earthquakes occur and how we can use improved knowledge to drive short-term and actionable forecasts of seismic activity. They expand the usefulness of critical earthquake products and advance the sophistication of those products to keep pace with the rapidly evolving needs of an ever-expanding user base while maintaining the position of the USGS as a global leader in earthquake science.

1. Focus on system-level science.
2. Establish an automated earthquake-processing pipeline.
3. Enhance the accuracy and reliability of the ShakeAlert Earthquake Early Warning system and plan for extension to other regions.
4. Implement time-dependent earthquake forecasting.
5. Develop physically realistic models.
6. Expand computational capacity.

This science strategy is organized into three primary sections. The first section provides an overview of the EHP and its budget, governance, and program council. Readers familiar with the program may wish to focus on the second section, which describes the core of the science strategy, including priorities across each of the EHP's major program activities in monitoring, hazard assessment, and targeted research. The third section outlines science priorities that cut across program activities, including those involving collaborations external to the EHP.

Introduction

Seismic risk is defined as the intersection between earthquake hazard and the exposure of a vulnerable population, or infrastructure, to that hazard. This concept has led to the popular adage that "earthquakes don't kill people; buildings do." Because earthquakes are a national hazard, and because almost half of the population of the United States is exposed to potentially damaging shaking (Jaiswal and others, 2023), the U.S. Congress has established the National Earthquake Hazards Reduction Program (NEHRP; formally the Earthquake Hazards Reduction Act of 1977; Public Law 95–124, 42 U.S.C. 7701 et. seq.) with the goal of reducing risks from future earthquakes and increasing the resilience of communities in the United States. NEHRP is periodically reauthorized by Congress, most recently in 2018 (Public Law 115–307). The U.S. Geological Survey (USGS) is one of four Federal partners within NEHRP; the others are NEHRP's lead agency, the National Institute of Standards and Technology (NIST), the Federal Emergency Management Agency (FEMA), and the National Science Foundation (NSF). The four agencies each have distinct responsibilities but work in close coordination to reduce the Nation's risks to life and property from earthquakes and increase the resilience of vulnerable communities. Working together, these agencies coordinate earthquake monitoring, research, assessments, risk reduction implementation measures, education, and outreach activities (NEHRP, 2023).

In 2023, the estimated annualized losses to the building stock from earthquakes in the United States were more than $14.7 billion (Jaiswal and others, 2023). This was an increase of 140 percent compared to previous estimates in 2017 (Jaiswal and others, 2017). Each year, more communities are put at risk because urban centers and populations continue to grow in regions of moderate-to-high earthquake hazard and because the infrastructure to service that population becomes more expensive. The USGS National Seismic Hazard Models (NSHMs) are the basis for the seismic provisions in building codes that underpin domestic construction efforts, currently estimated to cost $1.8 trillion per year (https://www.census.gov/construction/c30/c30index.html; U.S. Census Bureau, 2024). These statistics show that a lack earthquake preparedness is extremely costly; efforts to improve our Nation's resilience to earthquakes can bring a significant return on investment.

Building a society that is earthquake ready requires critical information. To help mitigate earthquake losses and reduce earthquake risk, the USGS Earthquake Hazards Program (EHP) is laying out a 10-year science strategy to guide the direction of the program, how its work is communicated, and how to provide earthquake information to those who need it most.

Earthquake Hazards Program Overview

The EHP fulfills USGS statutory responsibilities defined by the congressionally enacted Earthquake Hazards Reduction Act of 1977 and subsequent reauthorizations, most recently in 2018[1]. Under NEHRP, the USGS is responsible for reporting on significant domestic and international earthquakes and conducting research and other activities necessary to characterize and identify earthquake hazards, assess earthquake risks, monitor seismic activity, and improve earthquake forecasts. Within NEHRP, the USGS's EHP has roles that are national and sometimes global in scope, including

- Domestic earthquake monitoring and reporting using data and services from seismic and geodetic networks of the Advanced National Seismic System (ANSS), which involves partnerships between the National Earthquake Information Center (NEIC) and participating regional seismic networks (RSNs).
- Global earthquake monitoring and reporting through the operation and maintenance of the Global Seismographic Network (GSN), in partnership with the NSF and the NEIC, which functions as a 24/7 service dedicated to the rapid characterization of all significant earthquakes worldwide.
- State-of-the-art hazard assessments through maintenance and refinement of the NSHM, which is the basis for the seismic provisions incorporated into State and local building codes, the seismic design of engineered buildings and infrastructure, and a variety of risk mitigation tools.
- Targeted research to advance the understanding of earthquake processes, occurrence, and probabilities and to improve the NSHM, earthquake characterization, and other EHP products.
- An external grants program to support applied research needs of the EHP.

In the past decade, Congress has provided additional direction and funding to the USGS to support the development of an earthquake early warning (EEW) system for the West Coast called ShakeAlert, as a product of the ANSS. ShakeAlert is being developed and operated in partnership between the USGS EHP, States, and universities host RSNs. Public alerting for ShakeAlert has been operational in California since October 2019 and in Oregon and Washington since spring 2021.

The USGS real-time earthquake information products support public safety and Federal and State earthquake-response operations and are considered mission

[1]Earthquake Hazards Reduction Act of 1977 (Public Law 95–124, 42 U.S.C. 7701 et. seq.), as amended by Public Laws 101–614, 105–47, 106–503, and 108–360 with modifications made by Public Law 115–307.

Our Vision

Provide authoritative and indispensable research that can be successfully applied to reducing earthquake losses and improving resiliency in the United States and its territories

Our Mission

Distribute timely notifications of the location, source characteristics, and probable impact of significant earthquake occurrences

Provide early warning messages of damaging earthquake shaking for distribution by alert delivery partners

Provide quantitative assessments of earthquake hazards nationwide

Advance the understanding of earthquakes, their impacts, their source and seismic wave phenomena, and of earthquake risk and risk mitigation

Figure 1. Vision and mission statements for the U.S. Geological Survey Earthquake Hazards Program.

essential to the Department of the Interior (DOI). The USGS, through the EHP, supports DOI mission essential function 3–12 to "monitor domestic and global seismic activity and provide warnings, rapid information, and decision support products for situational awareness of earthquake impacts." DOI relies upon the EHP to provide scientific expertise and assistance for earthquakes and other natural hazards, including real-time earthquake information provided to emergency managers and other agencies.

Program Vision and Mission

The vision of the EHP (fig. 1) is to provide authoritative and indispensable research that can be successfully applied to reduce earthquake losses and improve resiliency in the United States and its territories. The EHP mission is to distribute timely notifications of the location, source characteristics, and probable impact of significant earthquake occurrences; provide early warning messages of damaging earthquake shaking for distribution by alert delivery partners; provide quantitative assessments of earthquake hazards nationwide; and advance the understanding of earthquakes, their impacts, their source and seismic wave phenomena, and earthquake risk and risk mitigation.

To accomplish its mission, the EHP and its partners operate seismic and geodetic monitoring systems, report on earthquakes and their impacts in near real-time, perform data analyses, carry out field studies, and conduct directed research. The program also supports the interests and policies of the U.S. Government abroad as a trusted source of information on seismic events and earthquake hazards and research. The EHP mission work is performed in partnership with other Federal and State agencies, academic institutions, and professional interests.

Earthquake Hazards Program Values

The EHP is committed to executing the work of the program in accordance with the USGS guiding principles (https://www.usgs.gov/human-capital/usgs-guiding-principles): to be respectful, be accountable, communicate effectively, value differences, collaborate, and advance the USGS mission. Diversity, equity, inclusion, and accessibility (DEIA), in line with broader USGS commitments, are core components of programmatic activities to advance hazard characterization and risk reduction for all communities and individuals across the Nation. The EHP works with an established and expanding list of partners to provide objective, impartial, and actionable science to stakeholders.

Earthquake Hazards Program Role Within the Natural Hazards Mission Area

The EHP sits organizationally within the USGS Natural Hazards Mission Area (NHMA). The NHMA has direct responsibility for five other hazards-focused programs: the GSN, Coastal and Marine Hazards and Resources, Landslide Hazards, Volcano Hazards, and Geomagnetism Programs. The GSN is directly related to the activities of the EHP, but is a separate line item in USGS annual appropriations, and is thus programmatically independent. In addition, the NHMA is responsible for coordinating and supporting the broader hazards mission of the USGS, including activities related to floods, hurricanes and severe storms, tsunamis, and wildfires, and implementation of the bureau's risk strategy. The NHMA also supports the USGS's internal emergency management functions for coordinating USGS response activities following disasters, potential disasters, and hazardous events.

Natural Hazards Mission Area Overview

The mission of the USGS in natural hazards is to develop and apply hazard science to help protect the safety, security, and economic well-being of the Nation. To meet this mission, the USGS conducts research to inform a broad range of planning and response activities at individual, local, State, national, and international levels. A resilient society requires a responsive government to reduce the loss of life and disruption caused by natural hazards. People who are potentially affected by natural hazards need robust assessments to prepare for hazardous events, and they need up-to-date information for situational awareness during times of hazard-related crises. To meet these needs, scientists, in turn, require fundamental understanding of natural processes and observations of natural events.

Natural Hazards Mission Area Science Strategy

The science strategy for the NHMA (Holmes and others, 2013) identified four goals for its future, which are outlined in figure 2.

Earthquake Hazards Program Role Within the National Earthquake Hazards Reduction Program

The USGS EHP is the applied Earth science component of NEHRP, (https://nehrp.gov) the four-agency partnership among the NIST, FEMA, NSF, and the USGS that was established by the Earthquake Hazards Reduction Act. The strategic vision of NEHRP is "a nation that is ready and capable to withstand, respond to, and recover from earthquakes and their consequences," and its mission is to "develop, advance, and disseminate knowledge, tools, practices, and policies to enhance the nation's capabilities to withstand, respond to, and recover from earthquakes and their consequences." (NEHRP, 2023, p. iii).

National Earthquake Hazards Reduction Program Strategic Plan

The NEHRP strategic plan (NEHRP, 2023) identifies a number of responsibilities for the USGS, within an overarching statement that the USGS "conducts and supports targeted geoscience research investigations on earthquake causes and effects, produces national and regional seismic hazard maps and assessments, monitors and rapidly reports on earthquakes and their shaking intensities and expected impacts, works to improve public understanding of earthquake hazards, and coordinates post-earthquake studies carried out and supported by NEHRP agencies and other organizations." (NEHRP, 2023, p. 3).

The plan identifies 4 strategic goals and 18 associated strategic objectives, which collectively represent the strategy of NEHRP over the coming 7-year period (fig. 3).

None of these goals/objectives are assigned to any one NEHRP agency; rather, the plan recognizes that each agency, to varying degrees, may have a role in each strategic effort and that agencies work collectively to achieve the goals.

The NEHRP strategic plan also identified an additional eight focus areas that require increased emphasis moving forward but that are dependent on the availability of associated resources:

NATIONAL HAZARDS MISSION AREA—STRATEGIC GOALS

Based on USGS Natural Hazards Science Strategy (USGS Circular 1383–F, Holmes and others [2013])

- Enhanced observations
- Improved fundamental understanding of hazards and impacts
- Improved assessment products and services
- Effective situational awareness

NATIONAL HAZARDS MISSION AREA—STRATEGIC ACTIONS

Prioritized based on the degree to which each action

- Helps meet USGS core responsibilities
- Helps the Federal Government to meet its responsibilities in the hazards arena
- Is important for risk reduction, protecting human health, the economy, or national security
- Addresses a large gap in hazards science understanding and reduces uncertainty
- Enhances areas where the USGS has a unique role and expertise
- Holds a high potential for investment return in the form of improved assessments and awareness

Figure 2. Strategic priorities of the U.S. Geological Survey (USGS) Natural Hazards Mission Area, as outlined in Circular 1383–F (Holmes and others, 2013).

NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM—STRATEGIC GOAL 1

Advance the understanding of earthquake processes and their consequences

OBJECTIVES

1.1: Advance the understanding of earthquake phenomena and the propagation of seismic energy

1.2: Advance the characterization of the Nation's seismicity, including sources, and seismic hazards

1.3: Advance seismic monitoring including improving, extending, and maintaining the Advanced National Seismic System

1.4: Advance the understanding of the consequences of earthquakes and associated hazards to society and the built environment

1.5: Advance the understanding of social, behavioral, and economic factors pertinent to implementation of earthquake preparedness, mitigation, and recovery strategies

NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM—STRATEGIC GOAL 2

Enhance existing and develop new information, tools, and practices for protecting the Nation from earthquake consequences

OBJECTIVES

2.1: Enhance current earthquake scenarios, risk assessment methodologies, and loss estimation tools to improve seismic risk information

2.2: Further develop and implement a West Coast earthquake early warning system and its associated communication, education, and outreach

2.3: Enhance and develop cost-effective tools and practices, including up-to-date building codes and national consensus standards, that improve the seismic performance of new and existing buildings and lifeline infrastructure

2.4: Advance knowledge to facilitate characterization of earthquake resilience and develop tools to measure successful implementation of resilience practices and policies

NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM—STRATEGIC GOAL 3

Promote the dissemination of knowledge and implementation of tools, practices, and policies that enhance strategies to withstand, respond to, and recover from earthquakes

OBJECTIVES

3.1: Enhance the accuracy, timeliness, usefulness, and accessibility of earthquake information products for a diverse range of users to better prepare for and respond to earthquakes

3.2: Implement and regularly update a National Seismic Hazard Model based on the latest research, source models, seismicity, and field studies essential for implementing state-of-the-art mitigation, design, and construction strategies

3.3: Actively engage in the continual development and use of up-to-date seismic design guidelines, standards, and building codes and advocate for their adoption and enforcement at the State and local level

3.4: Support and enhance earthquake education, emergency drills, and exercises to promote effective earthquake awareness as well as mitigation, response, and recovery planning

3.5: Promote the implementation of earthquake preparedness, safety, response, and recovery strategies

NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM—STRATEGIC GOAL 4

Learn from post-earthquake investigations to enhance the effectiveness of available information, tools, practices, and policies to improve earthquake resilience

OBJECTIVES

4.1: Maintain and advance program-wide procedures and policies for post-earthquake investigations and data acquisition management

4.2: Advance earthquake preparedness, safety, response, and recovery strategies by translating post-earthquake investigation results into approaches for improved resilience

4.3: Identify and take advantage of opportunities to collaborate on development of scientifically informed metrics and actions to evaluate community earthquake resilience after an earthquake

4.4: Provide mechanisms to promote relevant feedback to the public regarding lessons learned from earthquakes

Figure 3. Strategic priorities of the National Earthquake Hazards Reduction Program (2023).

1. Advance earthquake science for subduction zone regions.
2. Develop enhanced performance-based seismic design procedures and metrics for the functional recovery of buildings and lifeline infrastructure.
3. Advance performance-based seismic design and assessment methods to implement multisystem coordination.
4. Further expand EEW capabilities.
5. Develop consistent performance guidance for lifeline infrastructure.
6. Enhance guidance to ensure that information and tools effectively support the needs of those who implement mitigation, preparedness, and recovery measures.
7. Advance the science of earthquake sequence characterization.
8. Enhance risk reduction strategies for Federal agencies.

The USGS can play a key role in many of these, including subduction zone science (SZS), EEW, and earthquake sequence characterization. Further details can be found in the NEHRP plan (NEHRP, 2023).

Within the framework of NEHRP, USGS—and thus EHP—is also responsible for managing the coordination of post-earthquake investigations. USGS Circular 1242 (Holzer and others, 2003), “The Plan to Coordinate NEHRP Post-Earthquake Investigations,” provides a framework for this coordination by NEHRP agencies, which also involves certain partner organizations. The plan identifies roles and responsibilities, outlines procedures for how NEHRP agencies and their partners should interact when investigating earthquakes, and organizes domestic investigations and dissemination of results into a phased timeline. Although this plan has proven valuable in the 20 years since its publication, a lot has changed, including the activities of, and relationships between, the NEHRP agencies and other groups that participate in investigations. In light of these developments, the EHP has recently supported an update to this plan, in collaboration with the Applied Technology Council. The revision, published as USGS Circular 1542 (Poland and others, 2024), emphasizes the need for ongoing planning and exercising for effective interagency coordination and includes new guidance on social science and ethical considerations for investigations. The update is also intended to allow NEHRP and partner agencies to be more nimble in post-earthquake investigation coordination efforts in order to guide the response to a variety of earthquakes.

Earthquake Hazards Program Science Strategy

The following EHP science plans were recently completed and published, or remain in effect:

- “Advanced National Seismic System—Current status, development opportunities, and priorities for 2017–2027” (USGS, 2017).
- “U.S. Geological Survey National Strong-Motion Project Strategic Plan, 2017–22” (Aagaard and others, 2017).
- “Revised Technical Implementation Plan for the ShakeAlert System—An Earthquake Early Warning System for the West Coast of the United States” (Given and others, 2018).
- “Leveraging Geodetic Data to Reduce Losses from Earthquakes” (Murray and others, 2018).
- “National Earthquake Information Center Strategic Plan, 2019–23” (Hayes and others, 2019).
- “Induced Seismicity Strategic Vision” (Cochran and others, 2024).

Additional associated plans for NHMA-wide strategies include

- “Reducing Risk Where Tectonic Plates Collide—U.S. Geological Survey Subduction Zone Science Plan” (Gomberg and others, 2017). This plan provides guidance for how USGS science activities associated with subduction zone hazards and risks should be prioritized, including through the leveraging of partner activities in related science endeavors.
- “Science for a Risky World—A U.S. Geological Survey Plan for Risk Research and Applications” (Ludwig and others, 2018). This plan establishes a community of practice focused on risk research and applications to improve internal communication, collaboration, and resource sharing across the USGS. It also provides specific recommendations that address mechanisms to ensure that risk research and applications are supported, prioritized, and incorporated in USGS work.

Rather than replacing the existing suite of critical planning documents (and others in development), this program-level strategy builds from existing plans, acting to tie together these independent pieces into a unified document and vision. The program-level strategy is thus consistent with the priorities set out in existing plans, where there is overlap in time. The program strategy is also intended to focus on the highest priorities of the program, rather than being inclusive of all programmatic activities; thus, priorities may be expressed in the more focused plans listed previously that are not reflected here, which does not mean those items are not priorities within the scope of work they represent.

Earthquake Hazards Program Budget

The EHP receives funding that is a line item in the USGS annual appropriation from Congress. The EHP's budget is structured around three components, as summarized in table 1 for the fiscal year (FY) 2020–24 annual appropriations.

Earthquake Hazards Program Budget History

Over the past decade, EHP funding has grown by more than 75 percent. Although the budget has expanded over that period, much of that growth has been focused on congressionally directed specific initiatives. Beginning around 2015, Congress has provided specific funding direction to the program for targeted monitoring and reporting activities, most notably the development of ShakeAlert as a new product of the ANSS. Though this funding enables significant program investment, it also creates an imbalance toward monitoring activities, which in FY 2024, represent approximately two-thirds of the program budget. The value of ANSS monitoring and reporting in reducing earthquake loss for the Nation depends on robust hazard and risk assessments; as such, robust monitoring relies on robust research. For example, although ShakeAlert serves to warn of an imminent earthquake, research on earthquake processes and effects is needed to design buildings and infrastructure that can withstand such events. In short, both monitoring and research are needed to mitigate earthquake risk.

Core program budget growth has also not kept up with inflation. In fact, when adjusted for inflation, core program funding (excluding of initiatives like ShakeAlert) has been steadily declining for more than a decade (fig. 4), leading to a commensurate loss in staff because appropriated funding with specific line-item direction must be allocated to that directed activity. This creates a challenge for maintaining program capabilities, and in many instances prevents new hiring to replace retirements, leading to shrinking expertise across the EHP and skillsets that are only covered by one person in many areas of the program.

Earthquake Hazards Program Science Centers

The work of the EHP is executed through regionally managed and administered science centers, with strategic planning and budget formulation under the responsibility of the Earthquake Hazards Program office (EHPO), and through external partners supported by grants and cooperative agreements. The EHP-related work at the science centers and at external institutions is funded on an annual basis through the EHPO. The EHP council, composed of EHPO leadership, scientists, engineers, and managers representing each science center, works to ensure communication and cooperation on relevant issues. A program council is a USGS requirement that serves as both a resource and a mechanism for engagement in establishing direction and priorities, increasing communication between mission areas and regional representatives, and understanding requirements, existing capacities, future capabilities, and more.

The successful execution of this science strategy is critically dependent on adequate levels of scientific staff at these centers (fig. 5). Staffing levels are not only impacted by budget stressors discussed previously but also by an ongoing challenge to hire staff to fill vacant and funded positions. USGS hiring processes have slowed, and filling key positions, particularly within earthquake monitoring groups (and most notably in ShakeAlert) has in recent years taken significant amounts of time—close to a year or more in some extreme cases. A large backlog of vacancies exists and will likely continue at the current rate of hiring. Many of the strategic priorities outlined in this science strategy are dependent on addressing these human resource challenges.

Table 1. Total appropriated (enacted) funding (in thousands of U.S. dollars) for the U.S. Geological Survey Earthquake Hazards Program in fiscal years 2020–23.

[ANSS, Advanced National Seismic System]

Program subcomponents	Funding, in thousands of U.S. dollars per fiscal year				
	2020	2021	2022	2023	2024
Earthquake Hazards Program	84,903	85,403	90,037	92,651	92,651
Assessment and characterization of earthquake hazards and risk	14,300	15,800	15,800	16,376	16,376
Targeted research into earthquake causes and effects	13,303	13,303	13,603	13,630	13,630
ANSS monitoring and reporting of earthquake activity and crustal deformation	57,300	57,300	60,634	62,645	62,645

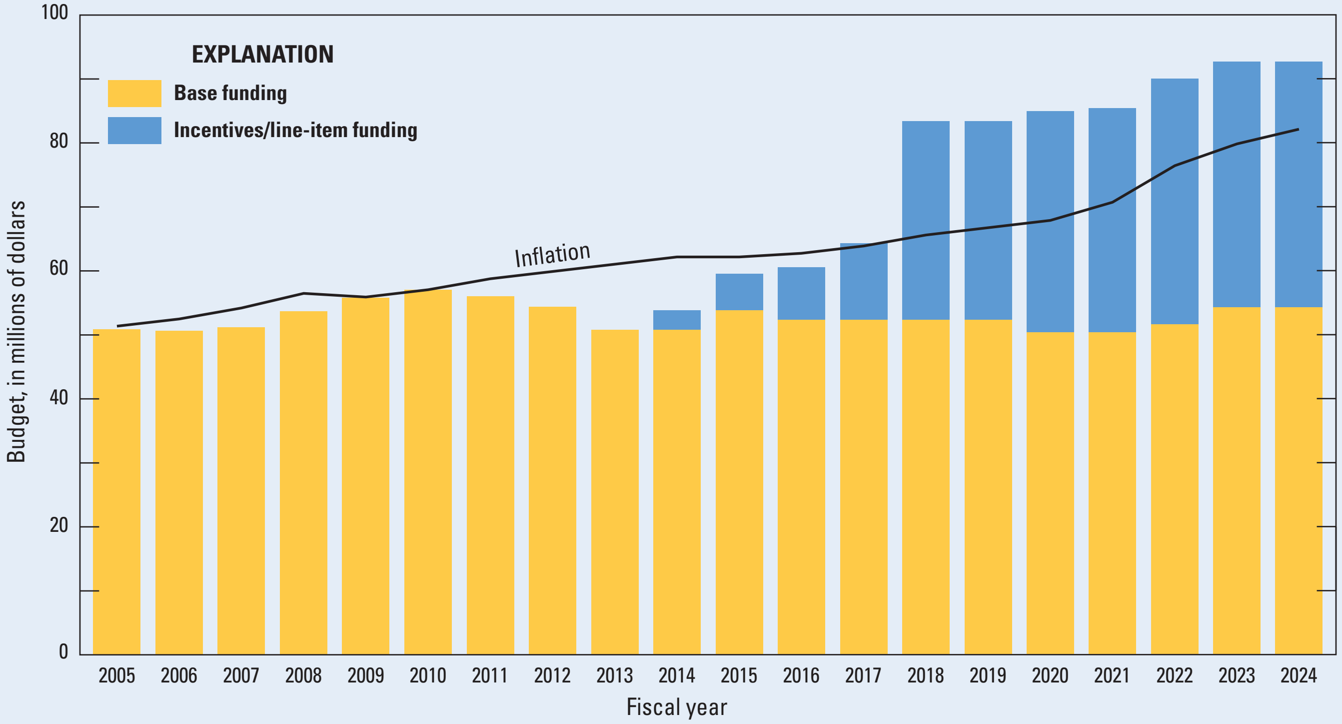
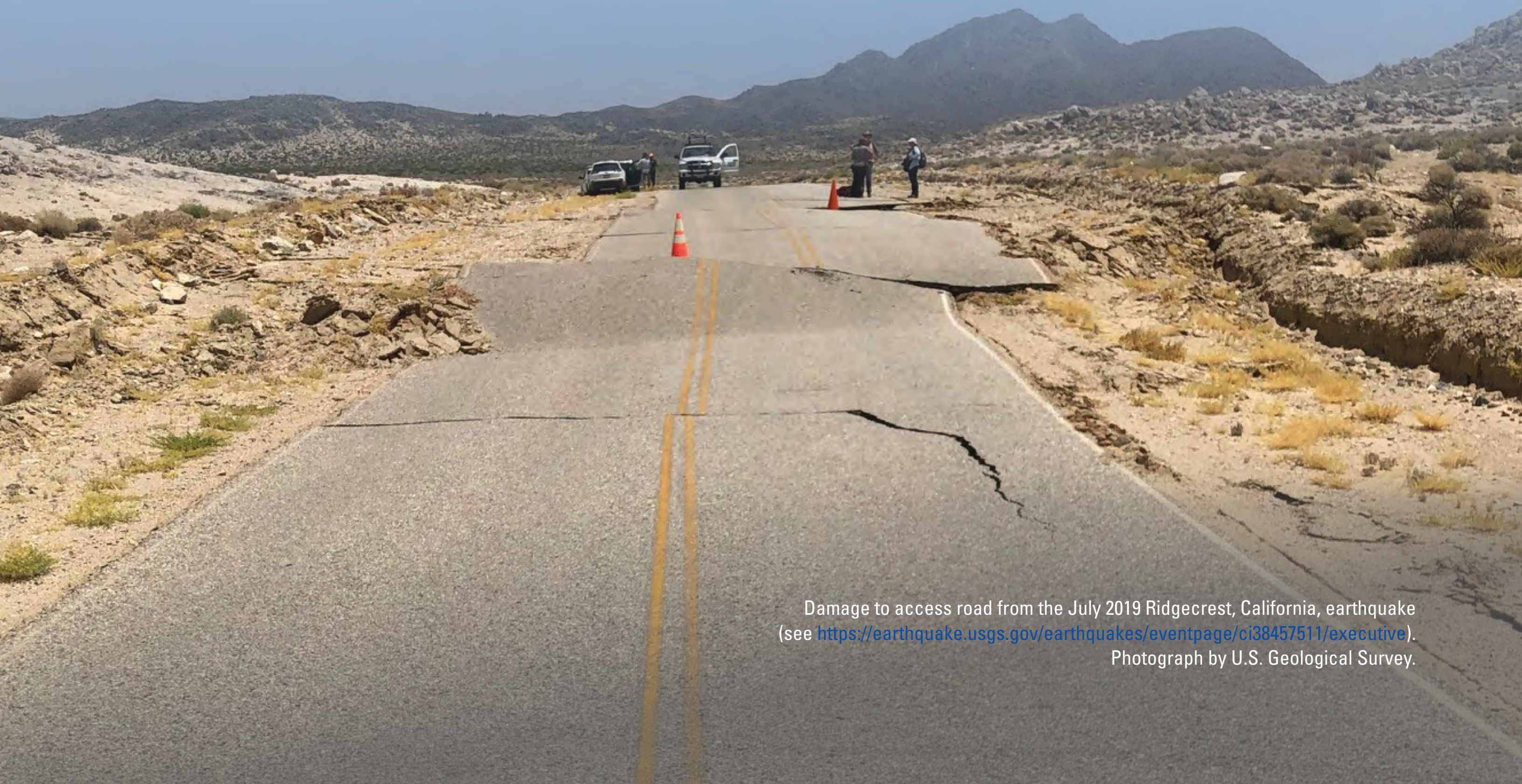


Figure 4. Earthquake Hazards Program budget history over the past two decades. Funding is separated here into base funding and initiatives or line-item funding, which comes with specific direction (for example, the ShakeAlert Earthquake Early Warning system). [Inflation measured using $1 in 2010 as a reference]



Damage to access road from the July 2019 Ridgecrest, California, earthquake (see https://earthquake.usgs.gov/earthquakes/eventpage/ci38457511/executive). Photograph by U.S. Geological Survey.

Earthquake Science Center

The Earthquake Science Center (ESC) has been a flagship research center for the U.S. Geological Survey (USGS) in the western United States for more than 50 years. The mission of the ESC is to collect a wide range of data on earthquakes, faults, and crustal deformation; to conduct research to increase our understanding of earthquake source processes, occurrence, and effects; and to synthesize this knowledge into seismic hazard assessments, aftershock forecasts, and ground-shaking scenarios for anticipated major earthquakes affecting the whole Nation. The ESC disseminates these data and products to a wide variety of stakeholders, including engineers and designers, emergency managers, owners and operators of lifelines[2], and the public, while also providing guidance and information for use in earthquake risk assessment and mitigation.

The ESC leads several thematic research projects and operational activities such as structural response monitoring and the ShakeAlert Earthquake Early Warning system, which takes advantage of robust and spatially distributed monitoring networks and is built upon existing infrastructure of the Advanced National Seismic System (ANSS). Seismic monitoring networks are operated in partnership with universities and State organizations and include the California Integrated Seismic Network, the Pacific Northwest Seismic Network, and geodetic networks throughout the western United States. The ESC's facilities also include renowned rock mechanics laboratories and deep borehole geophysics capabilities and provide support for extensive geophysical, geologic, and paleoseismic investigations along active faults. In addition to addressing nationally relevant issues, region-specific activities, such as those involving seismic networks and earthquake response, are accommodated by three offices strategically located in the San Francisco, Seattle, and Los Angeles areas. To fulfill its mission, the ESC engages in symbiotic partnerships that leverage complementary capabilities and resources with other USGS science centers, Federal and State agencies, private foundations, and public and private utilities and corporations.

[2]As used in this publication, the term lifelines refer to infrastructure, such as electric power, natural gas and liquid fuel, telecommunication, transportation, and water and wastewater systems.

Geologic Hazards Science Center

The Geologic Hazards Science Center (GHSC) conducts global investigations of earthquake, landslide, and geomagnetic hazards, executing four Department of the Interior mission-essential functions. The GHSC is home to the 24/7 National Earthquake Information Center (NEIC), the national center for the ANSS, which rapidly determines the location and size of destructive earthquakes worldwide and disseminates this information to national and international agencies, scientists, and the general public. The NEIC mission leverages the Global Seismographic Network, primarily operated through the GHSC at the Albuquerque Seismological Laboratory. NEIC's mission and accompanying ANSS product delivery and support are enhanced via in-house software and web development. The GHSC is responsible for leading the production of the National Seismic Hazard Model (NSHM), which quantifies the future likelihood of ground shaking from earthquakes and is used to guide building construction practice, insurance rate structures, and public policy assessments. Supporting the NSHM enterprise are three related teams: (1) earthquake geologists who focus on identifying and characterizing active faults across the United States using a variety of techniques to place those structures in a seismic hazard framework; (2) seismologists who develop predictive models of earthquake ground shaking, seismic wave propagation, and material properties that affect ground motions; and (3) civil engineers who serve as liaisons between the NSHM and the building-code community and who develop risk forecasts of earthquake-induced losses.

The GHSC is also the main science center for the Landslide Hazards Program, as well as for related research and monitoring that focus on landslide initiation processes, mobility, and magnitude. The GHSC is responsible for producing post wildfire debris-flow hazard assessments. GHSC landslide researchers leverage their expertise to support characterization of earthquake-triggered landslides, and they partner with scientists at the USGS Volcano Science Center to understand lahars and flank collapse processes. The GHSC also houses the Geomagnetism Program, which operates 14 magnetic observatories that are an integral part of the U.S. National Space Weather Strategy for monitoring and assessing space weather hazards that threaten important technological systems.

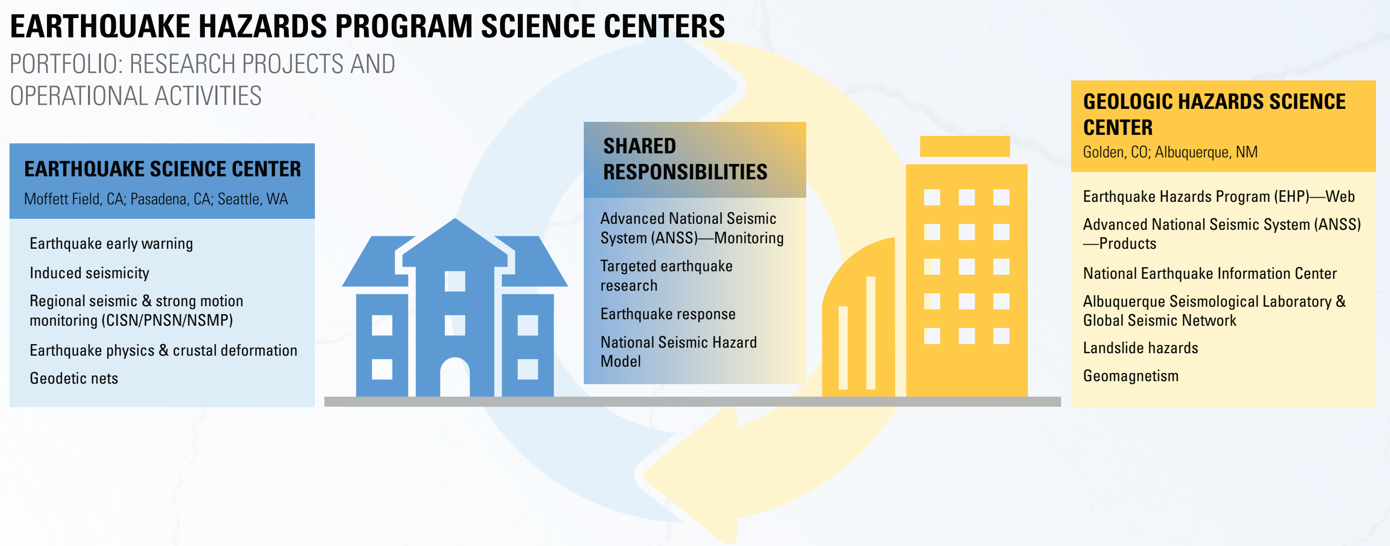


Figure 5. Internal work of the Earthquake Hazards Program is predominantly carried out at two science centers: the Earthquake Science Center and the Geologic Hazards Science Center. The Earthquake Hazards Program also provides some funding for work at the Alaska Science Center for focused efforts in the Alaska region (icons courtesy of artur80b—https://stock.adobe.com/). [CA, California; CO, Colorado; NM, New Mexico; WA, Washington; CISN, California Integrated Science Network; PNSN, Pacific Northwest Seismic Network; NSHM, National Seismic Hazard Model]

Earthquake Hazards Program Governance

The EHP includes both internal and external committee structures to ensure the efficient operation and strategic direction of the program. These committees each predominantly act in an advisory role to the EHPO, where final authority for programmatic direction lies. External advisory committees include the Scientific Earthquake Studies Advisory Committee (SESAC) and associated subcommittees, the National Earthquake Prediction Evaluation Council (NEPEC), the National Seismic Hazard Model Project Steering Committee (NSHMP-SC), and the Advanced National Seismic System Steering Committee (ANSS-SC). SESAC is a USGS Federal advisory committee established by NEHRP legislation. NEPEC, formerly an advisory committee established under the authority of President Carter, is now a subcommittee of SESAC.

Scientific Earthquake Studies Advisory Committee

The SESAC (https://www.usgs.gov/programs/earthquake-hazards/scientific-earthquake-studies-advisory-committee-sesac) was created in 2002 by legislation reauthorizing the NEHRP. The SESAC meets several times each year and provides advice and direction to the EHP. The committee's membership and procedures are compliant with the Federal Advisory Committee Act.

The SESAC advises the director of the USGS on matters relating to the USGS's participation in the NEHRP, including its roles, goals, and objectives within that program, its capabilities and research needs, guidance on achieving major objectives, and establishing and measuring performance goals. The SESAC issues an annual report to the director of the USGS for submission to Congress on or before September 30 of each year. The report describes SESAC activities and addresses policy issues or matters that affect the USGS's participation in NEHRP.

National Earthquake Prediction Evaluation Council

The NEPEC provides advice on earthquake predictions and related scientific research in support of the USGS's responsibilities under NEHRP to provide timely warnings of potential geological disasters. Until 2022, the NEPEC provided advice and recommendations directly to the director of the USGS, as a Federal advisory committee for the EHP alongside the SESAC. Now, the EHP has moved NEPEC under the SESAC, as a separate subcommittee providing advice to the program through that group. Like SESAC, NEPEC is advisory in nature and meets at least once per year.

National Seismic Hazard Model Project Steering Committee

The NSHMP-SC, which is also a SESAC subcommittee, was established to critique and review updates of the NSHMs and to provide overall guidance on the efforts of the NSHM project. The committee consists of nine subject matter experts from academia and industry. The NSHM project lead nominates the committee members, with input from the EHP coordinator. The members are selected based on their subject matter expertise, with each member representing a unique and critical component to the NSHMs. The steering committee chair serves as a member of SESAC.

Advanced National Seismic System Steering Committee

The final SESAC subcommittee, the ANSS-SC, was established to critique and review updates of the ANSS and to provide overall guidance on the monitoring efforts of the USGS EHP. The steering committee chair serves as a member of SESAC. The ANSS-SC consists of 10 subject matter experts representing the broader communities served by the organizations listed in this section. The members are each nominated by the relevant organization and approved by the ANSS coordinator, with input from the EHP coordinator. The members are selected on the basis of their subject matter expertise, and each member represents a unique and critical component and (or) stakeholder community of the ANSS.

- Consortium of Organizations for Strong Motion Observation Systems (known as COSMOS): one engineer
- Association of American State Geologists (known as AASG; https://www.stategeologists.org/): one State geologist
- National Emergency Management Association (known as NEMA; https://nemaweb.org/): one State emergency manager
- Earthquake Engineering Research Institute (known as EERI; https://eeri.org/): one geotechnical engineer; one research engineer; one structural engineer
- NSF National Geophysical Facility community representative (https://www.iris.edu/hq/): one research seismologist, one research geodesist
- Seismological Society of America (known as SSA; https://www.seismosoc.org/): one research seismologist
- USGS: one representative from the Geologic Hazards Science Center (GHSC), one representative from the Earthquake Science Center (ESC)

The Earthquake Early Warning External Working Group

The EEW external working group (EEWEWG) provides guidance on scientific, technical, and educational and outreach issues that affect the development, implementation, and use of the ShakeAlert Earthquake Early Warning system. The group also evaluates ShakeAlert system performance information. The EEWEWG provides guidance on development of ShakeAlert products, metrics, and standards, as well as on the design and timing of phased rollout, particularly when, where, and if the system has met operational and performance standards for alerting to specific end-users, industry sectors, and the general public. The EEWEWG also reviews issues raised by the USGS ANSS coordinator, the USGS EEW coordinator, and the USGS EEW internal working group. The EEWEWG is set up as a subcommittee under the ANSS-SC, the chair of which provides EEWEWG recommendations to the USGS EHP's main external advisory body, the SESAC.

The National Implementation Committee

The National Implementation Committee (NIC) is a long-standing committee of the ANSS that includes internal and external representatives of the RSNs supported by the EHP, the ANSS technical manager, a representative of the National Strong Motion Project (NSMP), a representative of the ShakeAlert Earthquake Early Warning project, and a representative of the NEIC. The NIC is an operational committee to help with national ANSS implementation that is both balanced and achievable and that is well integrated across the regions, follows consistent standards and protocols, and meets implementation and operational milestones and performance goals. The committee also hosts regular meetings that include a broader suite of seismic network managers and leadership. Although not a subcommittee of the Earthquake Hazards Program council (EHPC), the NIC includes USGS representation such that it serves the necessary roles of council-related ANSS coordination within the EHP. A USGS employee from the NIC serves as a member of the program council. The current membership of the NIC is listed at https://www.usgs.gov/programs/earthquake-hazards/science/anss-committees.

Earthquake Hazards Program Council

Internally, EHP activities are structured around the major roles fulfilled within NEHRP as outlined previously: monitoring, hazards assessment, and targeted research. The EHPC was recently restructured to better align with these program subcomponents, wherein each focus is represented by multiple seats on the council. Membership involves USGS staff from the science centers who serve to represent the internal roles outlined in figure 6. Together, these nine roles

EARTHQUAKE HAZARDS PROGRAM COUNCIL

ADVANCED NATIONAL SEISMIC SYSTEM

Represents the major, domestically focused monitoring efforts (seismic and real-time geodetic) for EHP as encompassed by the ANSS.

EARTHQUAKE EARLY WARNING

Represents ShakeAlert-related efforts within ANSS (seismic and real-time geodetic), including operations and research, and communication, education, outreach, and technical engagement.

EARTHQUAKE PRODUCTS

Represents high-level integration of the major outward-facing products across the entire program. A major focus of this position is to improve product integration across EHP and to improve consistency and reduce redundancy in product development. Software architecture, hardware, and support are also represented by this role.

HAZARD, IMPACTS, AND RISK

Represents research and development related to probabilistic forecasting, scenario, and event-specific models of earthquake ground shaking (including the National Seismic Hazard Model, or NSHM), secondary hazards (for example, ground failure), and earthquake impacts (for example, the Prompt Assessment of Global Earthquakes for Response, or PAGER). It also represents seismic risk reduction via building codes and other risk-reduction strategies.

EARTHQUAKE RUPTURE FORECASTING

Involves the development and deployment of earthquake rupture forecast models, which represent one of the two main modeling components used in seismic hazard and risk analyses. It also involves research related to earthquake occurrence and statistical seismology.

EARTHQUAKE SOURCE PROCESSES

Represents research involving field, laboratory, and modeling investigations of earthquake physics, source characteristics of natural and induced earthquakes, rupture initiation, rapid earthquake source characterization, geologic and hydrologic controls on earthquake rupture, and related research.

GROUND MOTION RESEARCH

Represents research involving the use of seismic instrumentation, field observations, and geophysical surveys to understand and model earthquake ground motions, including the effects of complex rupture process, interaction between 3D crustal structure and the wave field, and nonlinear response of soft soils. Resultant predictive ground motion models are one of the key components of many USGS products such as NSHM, ShakeMap, and ShakeAlert.

REGIONAL COORDINATION

Represents regional coordination and earthquake response across the United States and internationally, ensuring region-specific needs are represented, with the aim that an appropriate array of geographically focused program activities is retained.

GLOBAL MONITORING

Represents the global earthquake monitoring activities of the program, with particular focus on the GSN.

Figure 6. Internal coordination roles of the science coordination committee, which is part of the Earthquake Hazards Program council (icons courtesy of MacroOne and antto—https://stock.adobe.com/). [EHP, Earthquake Hazards Program; ANSS, Advanced National Seismic System; 3D, three dimensional; USGS, U.S. Geological Survey; NSHM, National Seismic Hazard Model; GSN, Global Seismographic Network]

make up the EHP science coordination committee (SCC). Many of these positions represent associated subcommittees, which are in turn made up of a broader collection of EHP scientists involved in the day-to-day activities related to that specific priority.

The SCC reports to EHP management through the management coordination committee (MCC), which is made up of the program coordinator, associate coordinators, science center management, and the SCC chair. The MCC executes the priorities of the program as a whole. The MCC and SCC together comprise the EHPC. This program council structure ensures the coordination of plans, work, and funding, and the joint participation of EHP scientists and program management promotes the collective exchange of progress, information, priorities, opportunities, and new concepts.

Earthquake Hazards Program External Assistance and Coordination

The EHP provides significant support for external partners, averaging a little more than $28 million annually over FYs 2021–24. Much of this—approximately $22 million—supports cooperative agreements with monitoring partners within the ANSS and ShakeAlert. The balance supports annual external grants, as well as a cooperative agreement with the Statewide (previously Southern) California Earthquake Center (SCEC), which the USGS has supported since SCEC's inception more than 30 years ago.

External grant funding is executed through the management of 10 research panels, which span each of the internal research focus areas outlined in figure 6 (hazard, impacts, and risk [HIR]; earthquake rupture forecasting [ERF]; earthquake source processes [ESP]; and ground-motion research), ShakeAlert, and 5 regional coordination areas (Southern California; Northern California; the Pacific Northwest and Alaska; the Intermountain West; and the Central and Eastern United States) represented by the regional coordination subcommittee also outlined in figure 6. The external grants coordinators managing these panel activities are either the same individuals occupying the internal coordination roles of the EHPC or work closely with them to ensure funded projects align with internal priorities. Activities are managed by the EHP associate coordinator for external research.

U.S. Geological Survey research geologist measuring surface displacement resulting from the July 2019 Ridgecrest, California, earthquake (see https://earthquake.usgs.gov/earthquakes/eventpage/ci38457511/executive). Photograph by Ryan Gold, U.S. Geological Survey.

The Decadal Science Strategy

This report outlines the strategic priorities of the EHP over the next 10 years. Hereafter referred to as “the science strategy,” it addresses foundational and aspirational priorities. Foundational priorities are the key current activities which must remain a focus in the future. Aspirational priorities include topics where the portfolio of activity might be expanded and new opportunities that could receive investment over the next decade, should budget opportunities arise. In every case, the goal is to deliver the science and products that enable the Nation to become more resilient to earthquakes and to reduce associated losses. The focus of the science strategy is to provide strategic priorities within a framework of achievable activities and projects under existing appropriated funding levels and resources (that is, the foundational priorities). The aspirational priorities would require increases in appropriated funding. The science strategy is structured around the three major subcomponents of the EHP described previously and the nine areas of focus represented by the SCC. Priorities are also addressed for several crosscutting activities, including partnerships with other USGS programs, external partnerships, SZS, social science, disaster assistance, broadening engagement through DEIA activities, and science communication.

Advanced National Seismic System Monitoring

The ANSS is a cooperative effort to collect and analyze data on earthquakes; issue timely, reliable notifications of their occurrence and impacts; and provide data for earthquake research, hazard, and risk assessment as a foundation for building an earthquake-resilient Nation. Deployment of the ANSS is focused on expanding and improving the performance and integration of ANSS-participating monitoring networks in the United States. The system includes a national ANSS “backbone” seismic network, the NEIC, participating RSNs that are operated by or in cooperation with partners, the N4 regional network (distributed across the Central and Eastern United States), the NSMP, and real-time global navigation satellite system (GNSS) geodetic networks.

The ANSS “backbone” network, consisting of 100 broadband seismic stations, provides a national framework for monitoring. RSNs, operated by both the USGS and external university and State partners, monitor active faults and ground shaking in much greater detail and accuracy than is possible with the national-scale network. Some RSNs perform local data analysis to generate earthquake information products in addition to data distribution and archiving. ANSS RSNs serve as State or local distribution points for information about earthquakes to the public, local and State agencies, and other regional interests. The EHP also supports several USGS and partner-operated geodetic networks and has been advancing the incorporation of real-time geodetic data into ANSS monitoring capabilities.

The ANSS can detect almost all felt earthquakes in the United States. Thanks to substantial improvements to station coverage and methods for rapid analysis, the ANSS now reports on significant domestic earthquakes within minutes of their occurrence and delivers a suite of informational products, providing situational awareness in near real-time. There is great demand for such information in times of crisis: after a large earthquake, ANSS websites can receive millions of visits, and https://earthquake.usgs.gov is one of the most heavily trafficked sites in the Federal Government (U.S. General Services Administration, 2024).

The highest priorities of the ANSS are guided by the ANSS-SC and the ANSS NIC, with USGS oversight. Major priorities for the system are described in USGS Circular 1429, “Advanced National Seismic System Current Status, Development Opportunities, and Priorities for 2017–2027” (USGS, 2017) and in USGS Circular 1457, “National Earthquake Information Center Strategic Plan, 2019–23” (Hayes and others, 2019). Circular 1429 (USGS, 2017) defines three thematic development opportunities: (1) ensuring readiness in an earthquake crisis, (2) advancing earthquake safety in urban areas, and (3) expanding the observational database for earthquake risk reduction.

ANSS is a large system, and its development opportunities overlap with the priorities of several SCC subcommittees (fig. 7). Overlapping areas of focus include ShakeAlert implementation and operation, GSN/NEIC modernization, aftershock forecasting, induced earthquake studies, detailed source characterization using seismic and geodetic data, earthquake damage and impact assessment, and ground-motion characterization. Monitoring priorities are mostly unique to the ANSS SCC subcommittee and are the focus of this section. The priorities listed here are informed by discussion with the NIC but are focused on needs of the USGS EHP. Where relevant, the priorities are referenced to their thematic development opportunities as listed in Circular 1429 (USGS, 2017). The priorities in this plan are not meant to replace the development opportunities in Circular 1429 (USGS, 2017) but to expand or highlight them given the evolving technologies and new possibilities.

Modernize Instrumentation and Improve Network Topology.—As reflected in the “Opportunity C” section of Circular 1429 (USGS, 2017), a core part of ANSS’s success is the robust collection and archival of seismic and real-time geodetic data. These data directly or indirectly affect almost all studies conducted under the EHP. ANSS is working towards intelligent, targeted improvements to its network topology, instrumentation, acquisition, and distribution. Outdated instrumentation, such as analog stations and some short-period sensors, should be upgraded or removed. Full implementation across the ANSS is currently aspirational, but **foundational** progress is possible using deferred maintenance funds and similar sources of funding (deferred maintenance

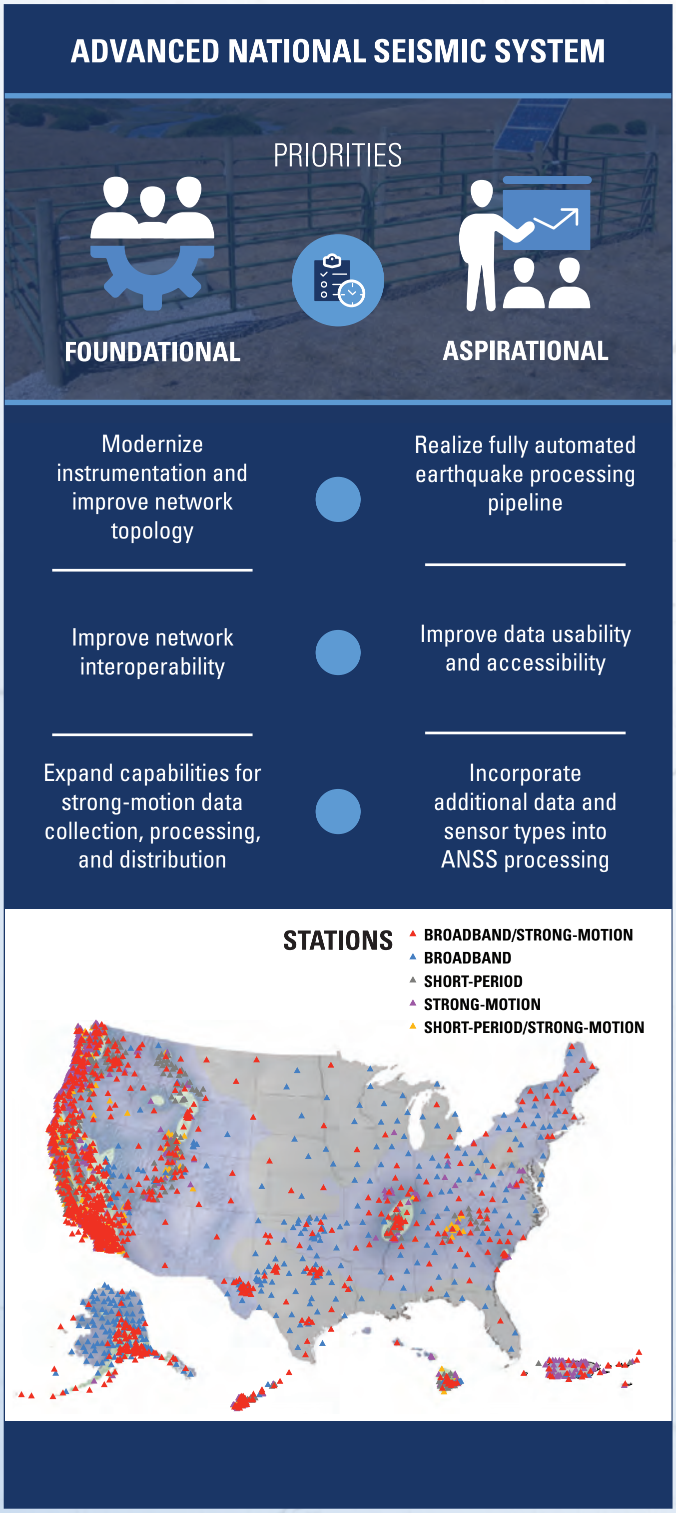


Figure 7. Advanced National Seismic System (ANSS) foundational and aspirational strategic priorities (map image courtesy of U.S. Geological Survey; icons courtesy of LineSolution—https://stock.adobe.com/).

is currently part of annual EHP appropriations), and by leveraging upgrades made as part of ShakeAlert Earthquake Early Warning buildout. Regions with large analog stocks include New Madrid, Northern California, Nevada, Pacific Northwest, and Utah. Across all of the ANSS, decisions on station upgrades, removal, or possible network expansion must be based on ANSS requirements, scientific benefits, and quantitative network assessments.

Improve Network Interoperability.—Aligning with the “Opportunity A” section in Circular1429 (USGS, 2017), the ANSS is a cooperative network that combines the strengths of university and government partners. To fully realize its potential, better coordination and network interoperability is essential. This is a **foundational** priority. Next generation earthquake processing systems and modifications to current systems must better facilitate interoperability and consistency in processing, including quality of source parameter estimations and associated uncertainties. These are essential to ensure that efforts such as the USGS NSHM project have access to consistent, high-quality data. ANSS uses international standards for distribution and archival of seismic data (for example, quakeML, miniSEED, and stationXML); however, for ANSS data and products to be most useful to the scientific and engineering communities, they must more carefully document details of their processing algorithms and more uniformly define metadata. Tabletop exercises are planned to be conducted with ANSS coordinators, the NEIC, and individual RSNs to test and improve standard operating procedures. The ANSS performance standards, originally defined 22 years ago, are planned to be updated to quantifiable metrics where appropriate. The goal is for these metrics to be tracked annually to assess improved performance. ANSS operations across all networks are planned to be examined to improve efficiency and robustness.

Expand Capabilities for Strong-Motion Data Collection, Processing, and Distribution.—In agreement with the “Opportunity C” section of Circular 1429 (USGS, 2017), a **foundational** priority for the ANSS is to explore leveraging partnerships to expand its distribution of accelerometers across networks and identify opportunities to improve or optimize station coverage. Development and modernization of automatic processing and dissemination of strong motion data from free-field sites and structures, leveraging new funding initiatives with partners as they arise, are part of this goal.

Realize a Fully Automated Earthquake Processing Pipeline.—Aligning with the “Opportunity A” section of Circular 1429 (USGS, 2017), seismology is on the cusp of a revolution. Using machine learning, university research groups are generating earthquake catalogs for target regions with lower magnitude thresholds and more accurate locations. Monitoring networks have implemented machine learning in their production seismic processing pipelines (for example, for pick classification), but most of the analysis for generating catalogs remains manual. Further applying machine learning techniques for seismic phase detection, identification, association, and timing in an operational environment will fundamentally change the way earthquakes have been processed over the past 50 years, potentially greatly reducing manual interaction. Refining, implementing, and verifying a fully automated system will be a large task beyond our current resources, but it has potential to lower costs and improve earthquake catalogs and thus is an **aspirational** priority.

Improve Data Usability and Accessibility.—Accessing USGS earthquake catalogs and waveform data can be arduous, requiring experienced seismological knowledge as well as a mix of modern and legacy software technologies and tools. Current data retrieval tools are slow, especially for the very large datasets required for development of machine learning techniques. In line with the "Opportunity C" section of Circular 1429 (USGS, 2017), some ANSS networks have been exploring the migration of data archives to the cloud, which may be a promising opportunity, though future cost is a large uncertainty. Although beyond current resources, providing better access to data, and access tools for data and data products, potentially cloud-based, that allow seismologists and others to efficiently conduct research and develop algorithms, will greatly facilitate future scientific advances, and is an **aspirational** priority of this plan.

Incorporate Additional Data and Sensor Types in ANSS Processing.—Currently, the ANSS leverages data beyond classical seismic data (most notably, ground- and space-based geodetic data, including real-time GNSS, optical imagery, and interferometric synthetic aperture radar [known as InSAR]), including data opportunistically retrieved from non-ANSS sources. These data can help improve fault rupture models, differentiate between mining activity and tectonic earthquakes, speed detection, produce faster and more robust magnitude estimates for the largest earthquakes, improve ground-motion estimates, and lower detection thresholds. Generally, these data are accessed via ad hoc methods by specialized researchers. In alignment with the "Opportunity C" section in Circular 1429 (USGS, 2017), an **aspirational** priority is to develop robust access methods and processing algorithms to improve basic monitoring and higher level products across the ANSS. Target data sources include class-C sensors, seismic arrays, ground- and space-based geodetic data, infrasound, and strain measurements from distributed acoustic sensing (DAS).

U.S. Geological Survey research geologists extract sediment core from Wade Lake, Montana, July 29, 2023. Photograph by Chris DuRoss, U.S. Geological Survey.

ShakeAlert

EEW is the capability to quickly and automatically identify and characterize an earthquake after it begins, estimate the intensity of ground shaking that is expected to result, and potentially deliver seconds of warning to people and systems that may experience damaging shaking. Recent Federal, State, and private investments have resulted in a West Coast EEW system (in California, Oregon, and Washington) called ShakeAlert, which began sending messages for public alerts throughout California in October 2019 and in Washington and Oregon in spring 2021.

The USGS EHP, with its State, university, and nonprofit partners, is working to complete the buildout of the ShakeAlert system for the U.S. West Coast. The USGS manages the ShakeAlert system, but the continued expansion and sustained value of ShakeAlert depends on the collaborative support of public, private, philanthropic, and academic partners. States participate in and contribute toward ShakeAlert implementation as they do for routine earthquake monitoring and other earthquake hazard mitigation activities. The State of California made EEW a priority in 2016 by enacting legislation that created the California Earthquake Early Warning Program (see https://earthquake.ca.gov/) within the Governor's Office of Emergency Services (known as Cal OES). The ShakeAlert system is being built by expanding and upgrading the infrastructure of RSNs that are part of the ANSS, the Pacific Northwest Seismic Network and the California Integrated Seismic Network, as well as real-time geodetic networks. The ShakeAlert system issues data packages, called ShakeAlert messages. These ShakeAlert Messages are then used by USGS-licensed technical partners for the delivery of ShakeAlert-powered products and services, such as an alert. Such technical partners are integral to the success of ShakeAlert by building systems that deliver alerts and automate actions. ShakeAlert is adding more seismic stations to complete buildout in 2025 and requires additional development to maximize its speed, reliability, and accuracy. Once buildout is complete, ShakeAlert will also need sufficient support for operation and maintenance of the expanded system to sustain its alerting capabilities. The priorities shown in figure 8 (not necessarily in priority order) articulate ShakeAlert goals for the next decade.

Complete Buildout of Seismic Station Infrastructure.—About 90 percent of the ShakeAlert seismic network was built at the end of 2023. Approximately 1,500 of the 1,675 stations called for in the 2018 technical implementation plan (Given and others, 2018) have been completed. The USGS and its ANSS partners have committed to completion of network buildout by the end of 2025, and this remains a **foundational** priority. After 2025, both USGS and university RSN operators must shift from the buildout mode of the past several years to a long-term sustainable operations and maintenance mode. This will require changes to work patterns, as well as budget

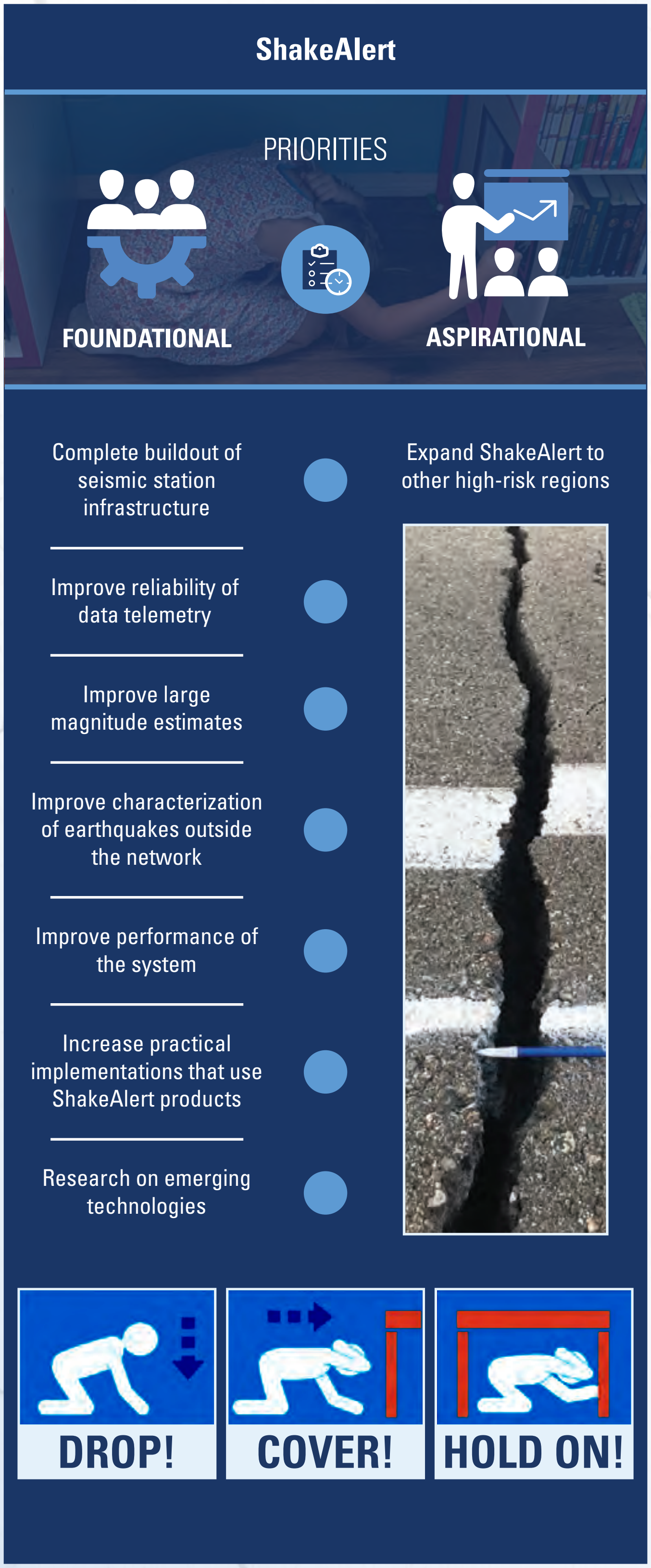


Figure 8. ShakeAlert foundational and aspirational strategic priorities (images courtesy of Earthquake Country Alliance; icons courtesy of LineSolution—https://stock.adobe.com/).

Northridge parking garage as a result of the January 17, 1994, magnitude 6.7 Northridge, California, earthquake. Photograph by U.S. Geological Survey.

and staffing models. Also, some adjustments to the topology of the sensor network will be needed to meet data quality standards and optimize the performance of the system.

Improve Reliability of Data Telemetry.—Additional planning and work can improve the reliability of telemetry infrastructure. In some cases, States are providing access to their microwave networks, for improved telemetry, at no cost. The technical implementation plan explained the need for reliable telemetry, both from the field and among data centers (Given and others, 2018), though those costs were not included in the 2018 cost estimate for the overall system of $28.6 million. In 2022, the ShakeAlert project commissioned a telemetry improvement study, which provided recommendations that can be used as the basis for future telemetry planning and work. A **foundational** priority is for ShakeAlert to create a telemetry improvement plan that describes both incremental progress that can be made within the existing operations and maintenance budget as well as more ambitious aspirational priorities that could be achieved with significant additional funding.

Improve Large Magnitude Estimates.—The ShakeAlert production system processes data and uses sophisticated computer algorithms to detect an earthquake, calculate its location and magnitude, and estimate the resulting intensity of shaking. Testing has shown that the current production system's two seismic algorithms to determine earthquake location and magnitude produce magnitude estimates that saturate at high magnitudes. The EPIC algorithm (Chung and others, 2019) saturates at a magnitude of about 7.0, and the FinDer algorithm (Böse and others, 2023) saturates at a magnitude of about 9.0. A **foundational** priority is for ShakeAlert to work to improve its capabilities to determine larger earthquake magnitudes more accurately. Steps include use of specialized fault-specific templates by FinDer that integrate a third algorithm, named GFAST-PGD (Murray and others, 2023), which uses geodetic data to determine magnitudes of 7.5 and larger.

Improve Characterization of Earthquakes Outside the Network.—Major earthquake sources that threaten Oregon, Washington, and California exist outside the ShakeAlert network footprint (for example, offshore and in Mexico, Canada, and Nevada) where it is difficult to determine accurate locations and magnitudes. Mitigating this problem requires **foundational** work on several fronts. Priorities discussed previously contribute—both by completing the station buildout and by improving the capabilities of current production algorithms—by adding fault-specific templates for offshore and across-borders events. Synthetic tests also demonstrate that the use of a specialized type of seismic station geometry, known as small-aperture arrays (a group of several seismometers spaced very closely together), can improve out-of-network locations. ShakeAlert has begun a project to collect a 2-year dataset from two temporary small-aperture arrays to test the ability of coastal arrays to improve EEW performance offshore. If successful and cost-effective, such arrays can be strategically added to the system. ShakeAlert plans to continue collaborating with the developing Canadian EEW system, importing additional station data as that is built out, and integrating processing and alerting between it and ShakeAlert.

Improve Performance of the ShakeAlert System.—A **foundational** priority is to improve the speed, accuracy, and reliability of the ShakeAlert system. Testing and operational experience can be used to inform improvements to the current production algorithms and alerting strategies. The ShakeAlert project plans to continue development, testing, and integration of geodetic methods for better magnitude estimates at magnitudes of 7.5 and larger, as described previously. Efforts also focus on continuing to improve direct use of ground-motion observations to forward-predict ground motions (Cochran and others, 2022) by adding attenuation and use of deep learning; these approaches can be integrated with the system if they improve the overall performance. This work includes development of a ground-motion aggregator to combine source-based and ground-motion-based earthquake characterization algorithms, research to improve ground-motion estimates through use of specific ground-motion models (GMMs) for various region and source types (called “nonergodic” GMMs), and development of specialized or hybrid GMMs. The project also plans to investigate approaches to reducing ground-motion uncertainties by implementing a more complex model with source, path, or site-specific terms. Data from offline ShakeAlert system testing and performance runs and production system results can be used to evaluate performance, fine-tune system parameters, find weakness or bugs in system modules, and inform changes to alerting products and strategies. Finally, continuously evaluating products and alerting strategies can help to achieve the greatest possible benefit for the greatest number of people and technical use cases.

Increase Practical Implementations that Use ShakeAlert Products.—The ultimate success of ShakeAlert depends on education and technical engagement with end users who will create and support practical implementations of ShakeAlert Messages for automated actions and human alerting, reinforced by correctly targeted communication strategies. It is a **foundational** priority to execute the recently completed “Communication, Education, Outreach & Technical Engagement (CEO&TE) Strategic Plan” and complete development of a technical/industry engagement strategy that lays out a strategy and action plan for recruiting technical partners in communications, manufacturing, infrastructure, technology, and other key industries that can directly benefit from EEW or will develop ShakeAlert-powered products and services for clients.

Research on Emerging Technologies.—A **foundational** priority of the ShakeAlert project is to research new technologies that have the potential to improve and advance EEW. These include DAS, integration of low-cost sensors and Internet of Things devices, seismogeodetic techniques, machine learning, and other technologies that may arise. Operational implementation of resulting research would require additional funding.

Expand ShakeAlert to Other High-Risk Regions in the United States.—Expansion of ShakeAlert into other high-risk regions in the United States would require Congressional direction and funding to EHP for that purpose, and thus, it is an **aspirational** priority. Possibilities could include the populated areas of western Nevada (Reno-Carson City and Las Vegas), Alaska, Utah, the New Madrid Seismic Zone, the Puerto Rico region, and elsewhere. The designs for expansion may require different approaches, such as use of low-cost sensors to augment some networks or different alerting goals tailored for the region. The ShakeAlert project plans to continue to collaborate with Natural Resources Canada as they implement an interconnected ShakeAlert system in Canada, and the project aims to seek ways to support the Centro de Investigación Científica y de Educación Superior de Ensenada (known as CICESE, or in English, the Center for Scientific Research and Higher Education at Ensenada**)** in Baja California, Mexico, to improve and reduce latency in the data they share via bilateral efforts.

Earthquake Products

Key to fulfilling the EHP mission to reduce losses associated with earthquakes is the capability to deliver actionable information to decision makers, partners, and the public. The EHP achieves this mission through the generation of a broad suite of public-facing hazard, risk, forecast, education, and post-earthquake products (fig. 9). These include the NHSM and maps, the result of NSHM efforts outlined in this section, and post-earthquake situational-awareness products like ShakeMap and PAGER (Prompt Assessment of Global Earthquakes for Response), which, respectively, describe the expected shaking intensity in the epicentral region of a recent earthquake and estimate the impact that shaking is likely to have on people and infrastructure.

The USGS EHP is recognized as a leader and expert for scientific hazard information in the United States and the world. To maintain—and continue to increase—effectiveness and recognition in today’s information spaces, it is essential that the EHP continue to improve the speed, access, quality, and interoperability of our scientific data and products. The integrated products team (IPT) serves an important role in these endeavors by providing a forum for product advocacy and review, identifying common themes and avenues for standardization across products, establishing well documented and standardized product reviews, and suggesting quality standards and benchmarks. Additionally, the IPT is a platform to share and build upon the knowledge and experience of many to increase overall impacts of all EHP products. The IPT has identified the following topics as priority efforts for the next decade (fig. 10).

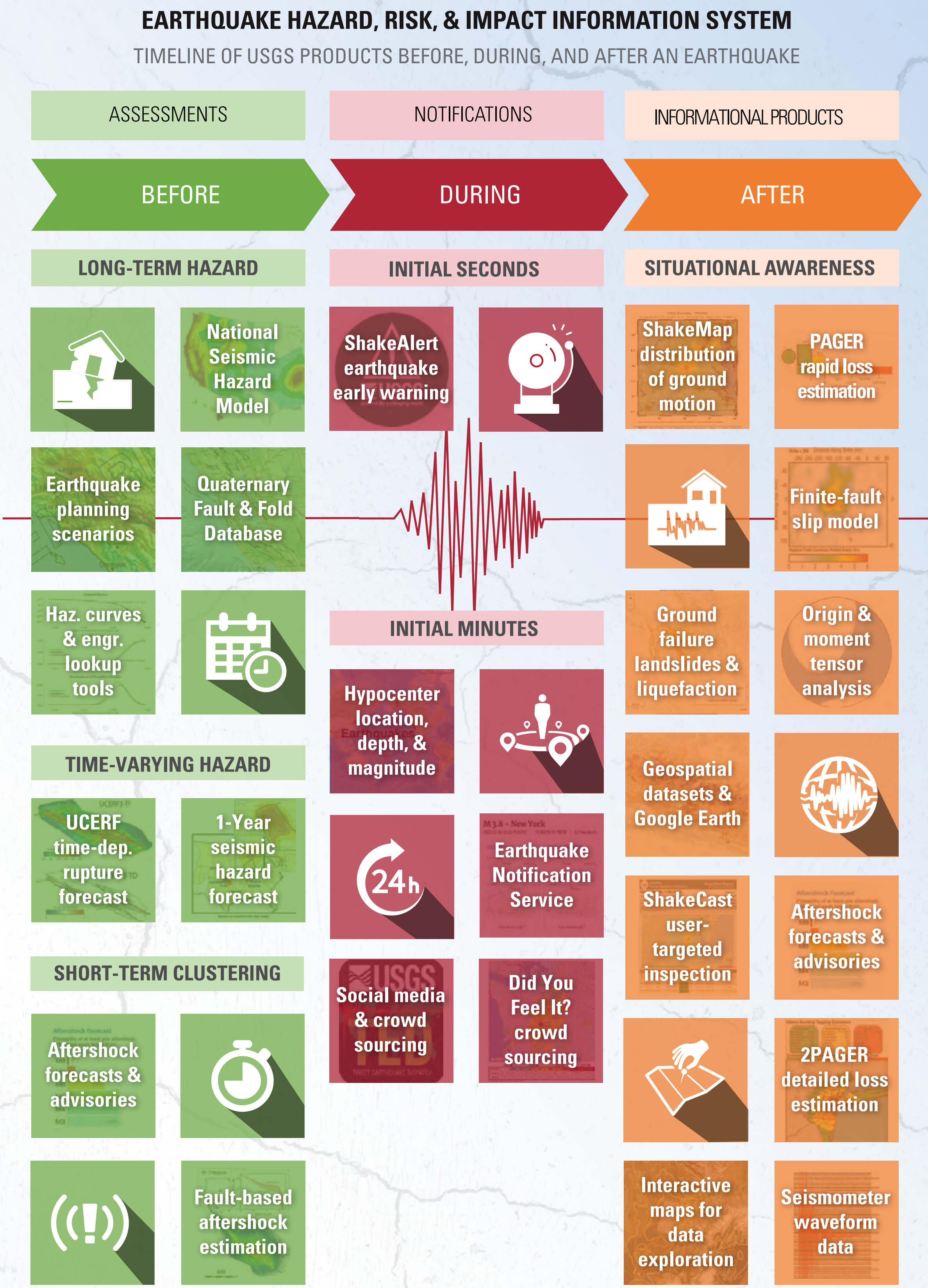


Figure 9. Core products of the Earthquake Hazards Program, displayed on a timeline reflecting the relevance and timeliness of products in relation to a recent significant earthquake (icons courtesy of SUE, jacartoon, ronnarid, and antto—https://stock.adobe.com/). [USGS, U.S. Geological Survey; Haz., Hazard; Engr., Engineering; UCERF, Uniform California Earthquake Rupture Forecast; Dep., Dependent; PAGER, Prompt Assessment of Global Earthquakes for Response]

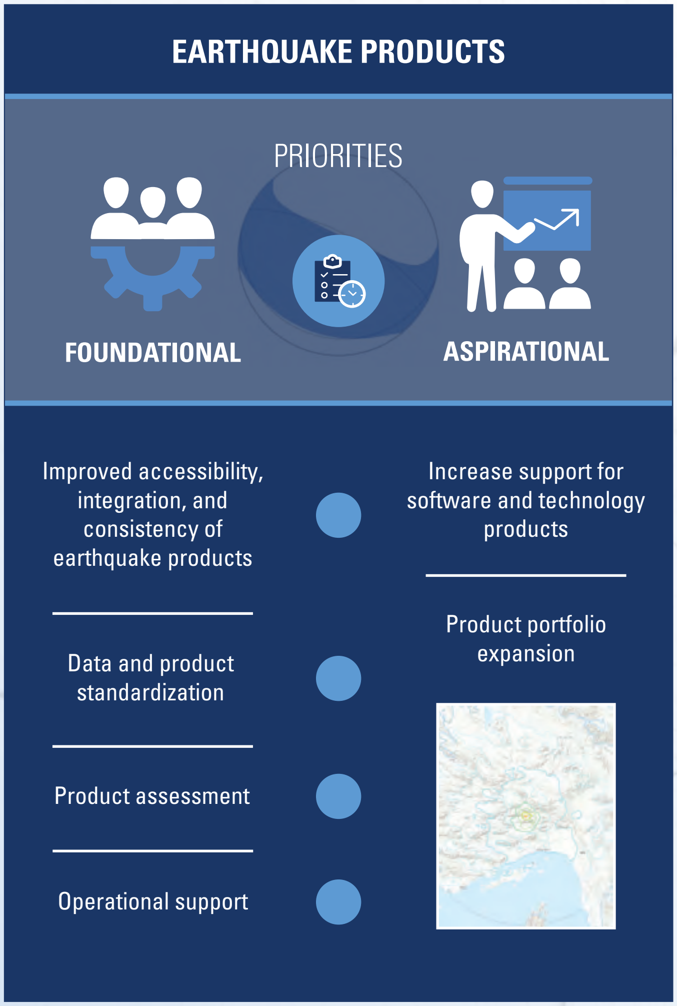


Figure 10. The integrated products team foundational and aspirational strategic priorities (map image courtesy of U.S. Geological Survey; icons courtesy of LineSolution—https://stock.adobe.com/).

Improved Accessibility, Integration, and Consistency of EHP Products.—The success and impact of EHP products are fundamentally rooted in their accessibility and usability among the diverse and evolving group of stakeholders and users that depend on EHP information. Improved consistency across all products increases a consumer's ability to understand and use the data. EHP stakeholder groups can be effectively served through increasing awareness of products, transparency in data and the methods used to create products, and application of data and product standards. Accessibility reflects the capability of a stakeholder to understand, apply, and benefit from an EHP product or from a collection of products. Accessibility improvements can be realized in many common EHP products such as derived seismic data, the NSHM, operational aftershock forecasting (OAF), and ground-motion research. Accessibility is significantly improved by consistency, data integration, and data standards, and the IPT facilitates these qualities across the EHP product suite. Integration of EHP products reflects both the notion that various EHP products directly and indirectly (interpretively) inform each other and that improved integration of currently disparate EHP products can lead to a more cohesive and self-consistent suite of stakeholder products. Accessibility to complex data via extensible and forward-looking tools, such as the ANSS comprehensive catalog (known as ComCat), can be simplified and directed to further support specific science goals such as NSHM. These are **foundational** priorities for the IPT.

Data and Product Standardization.—To maintain and continue to increase the impact and recognition of EHP in today's rapid digital information spaces, it is a **foundational** priority to create, adopt, and share standardized formats, distribution mechanisms, and development approaches. This will also improve data integration opportunities within the NHMA, with the USGS, and with our numerous partners to support scientists in asking bigger and broader questions that benefit from interdisciplinary data. The establishment of a full product life cycle review process can significantly increase awareness of existing standards and guidance on how best to achieve these standards. These data standards include data management principles, which are essential as our data volumes continue to grow, and facilitate the incorporation of findable, accessible, interoperable, reusable (referred to as "FAIR") data principles. Data and product integration examples include combined use of geodetic and seismic data in finite fault modeling and integrated modeling for hazard and impact. In the long term, as we focus on accessibility, integration, and standards, we create opportunities for scientists to explore new approaches and ideas. Additionally, the EHP actively participates in international standards working groups to keep the standards up to date and advancing, often providing guiding frameworks. An example is ground-motion-data processing proposals to make derived data more useable by, and accessible to, the broader scientific community.

EHP Product Assessment.—Increased focus on meeting user/consumer needs and maintaining engagement is a foundational priority, and this focus can help the EHP better understand and explore product impact prior to development and to, in turn, increase the impact of products that are implemented and released. This product assessment process directly supports the USGS's status as a recognized and sought-after scientific resource. Key components of this task are to jointly engage stakeholders and social scientists and to conduct regular and standardized product assessments as a means to collect information on the efficacy, usability, and accessibility of EHP products, identify unaddressed needs, and identify obsolete products that currently consume resources. Though progress can be made under current resources, full achievement of this priority is dependent on staffing in the social sciences as discussed in the "Crosscutting Activities" section of this plan.

Operational Support.—Improved support of existing operations is in alignment with USGS information management and technology goals (for example, see USGS Circular 1476 [USGS, 2021]). It is a **foundational** priority to develop and maintain robust architecture and infrastructure that leads to rapid and reliable delivery of actionable intelligence. This includes the use of infrastructure as code, which is a process for managing and provisioning computer infrastructure and resources through machine-readable definition files, or code, rather than physical hardware configuration or manually interactive configuration tools. Because infrastructure as code is version-controlled code, the computer infrastructure that it configures is the same every time, in every environment, and is automatable. This makes many associated tasks easier, including reproducibility and rapid deployment of fixes, improving automated system monitoring, implementing updates discovered through system evaluation, more routine code reviews on all software projects, and taking the time to learn about and consider new technologies that may benefit the program, including faster response time to requests. Keeping up with the evolution of technology is essential to ensure the USGS's scientific information is available and accessible across information platforms. This means both building and maintaining a USGS on-premise computer infrastructure as well as using offsite services through cloud providers.

Increase Support for Software and Technology Products.—An **aspirational** strategy to improve operational support goals more rapidly would be to systematically increase support for software and technology products, ideally with staff who have a passion for the mission of the EHP.

Product Portfolio Expansion.—Scientific and technological innovation will continue to rapidly evolve, and EHP will benefit from the capability to nimbly and effectively respond to these advances to support EHP research and operations. This ultimately (ideally) means more staff working on product implementation and operationalization. This can be in the form of increased development contributions from scientists or additional software development staff—an **aspirational** priority. As technologies change and improve, some approaches can become obsolete. The IPT will also work to evaluate existing products relative to a changing landscape and assess improvements or whether end of life should be considered, to maintain a high quality of delivery and effectiveness. Applying standardized best practices and approaches can improve overall quality and maintainability.

Targeted Research into Earthquake Causes and Effects

The EHP develops and applies targeted research to help protect the safety, security, and economic well-being of the Nation. This targeted research informs a broad range of planning and response activities at individual, local, State, national, and international levels. Over the lifetime of the EHP, important advances have been made in the ability to identify and forecast hazards associated with damaging earthquakes. Many of these advances have their roots in laboratory and theoretical developments focused on understanding the basic physical processes associated with earthquakes. To expand upon this success, the USGS plans to continue to conduct and support research on the causes, characteristics, and effects of earthquakes, prioritizing work that has direct application in increasing the accuracy and precision of the agency's earthquake hazards assessments, earthquake forecasts, and earthquake monitoring and situational-awareness products and that supports the Nation's earthquake mitigation practices. Overarching themes include (1) the development of quantitative, predictive, physics-based models of the geological settings, tectonic forces, fault characteristics, and faulting and wave-propagation processes that cause earthquakes and the resulting ground shaking and impacts and (2) expansion and refinement of observations to support those models, including observations of rock and fault properties, physical conditions within fault zones, crustal strain and deformation, and strong ground motions in various geological settings. Specific areas of focus include research on (human-) induced seismicity, forecasting hazards from earthquake sequences (the change in earthquake likelihood with time), characterizing crustal deformation, improving our understanding and modeling of earthquake ground motions, translating hazard into risk, and support for external research partnerships. Within the SCC, these activities are represented through four roles, discussed in more detail in the next section.

Earthquake Rupture Forecasting

Earthquake rupture forecasts (ERFs) are one of two main modeling components used in seismic hazard and risk assessments (the other component being a GMM). An ERF, also referred to as a "seismic source characterization" in some analyses, gives the probability of every possible fault rupture in a region and over a specified timespan (or a suite of synthetic catalogs of such events). The ERFs used in the USGS NSHM have traditionally been time independent (that is, ignoring any direct influence from past events), which is adequate when considering hazard over the 50-year lifetime of a typical building. However, there is increasing demand for more time-dependent models, which would account for the notion that (1) stress relaxation after a large event reduces the likelihood of another large event on the same section of fault until tectonic stresses have reaccumulated, and (2) aftershocks follow virtually every earthquake that occurs, and about 5 percent of these will be larger than the main shock and therefore potentially damaging. The latter can lead to a spatiotemporal clustering of earthquakes that can be quite significant with respect to earthquake insurance and other risk mitigation efforts. Modeling such effects is an ongoing effort and a challenge, but these models provide a more realistic accounting of the time evolution of seismic hazard. ERFs could also support other products, including operational earthquake forecasting (OEF), which would provide real-time updates on earthquake probabilities in support of situational awareness. An additional goal is to create a living research model that would enable more continual updates within the NSHM framework than have traditionally been achieved. Efforts in this topical area target the development and deployment of ERFs based on "best available science," whereas the basic research underpinning these models is the purview of the ESP subcommittee. The following are associated strategic priorities (fig. 11).

Support and Improve Deformation Models.—Deformation models provide estimates of slip rates on faults, and sometimes also "off-fault" deformation rates, based on both geologic and geodetic constraints. They are one of the most consequential and least well constrained elements of seismic hazard assessment. More specifically, it is not clear whether the models underlying the 2023 NSHM update adequately represent the range of viable models (that is, the complete range of models that fit the data constraints equally well). Furthermore, some models are maintained by individual researchers outside of the USGS, which may lead to reproducibility issues in the future. As a **foundational** priority, the EHP seeks to establish stable support for maintenance of currently used deformation models, encourage the development of others, and improve quantification of uncertainties both within and between different models. The EHP also aims to improve the reliability of off-fault deformation estimates. An **aspirational** priority is the internal implementation of all current deformation models such that associated codes can be operated and managed by multiple individuals, improving the robustness of the end-to-end hazard characterization framework.

Address Sampling Errors in Historical Seismicity.—A standard element of ERF development is to use historical and instrumental seismicity to infer the spatial distribution of long-term earthquake rates. Such estimates are currently limited by large changes in inferred hazard from relatively minor changes to the earthquake catalog (for example, magnitude estimate improvement with time). This instability stems from the fact that we are inferring long-term rates from a single historical catalog and that an alternative historical catalog would lead to a somewhat different result. EHP research has not yet been able to quantify this important sampling error. Doing so requires operationalizing the associated processing codes so they could be run over thousands of synthetic historical seismicity samples. This code operationalization is a **foundational** priority because timely and simultaneous model updates and overall reproducibility depend on this effort.

Deploy a Uniform, Nationwide Time-Dependent ERF.—The ERF models released as part of the NSHM have generally been time independent, especially with respect to spatiotemporal clustering. Recent scientific progress and feasibility demonstrations put the development and deployment of fully time-dependent nationwide models within reach, and at the same time, there is increasing demand for such models from some user communities (for example, for earthquake insurance, catastrophic bond markets, and

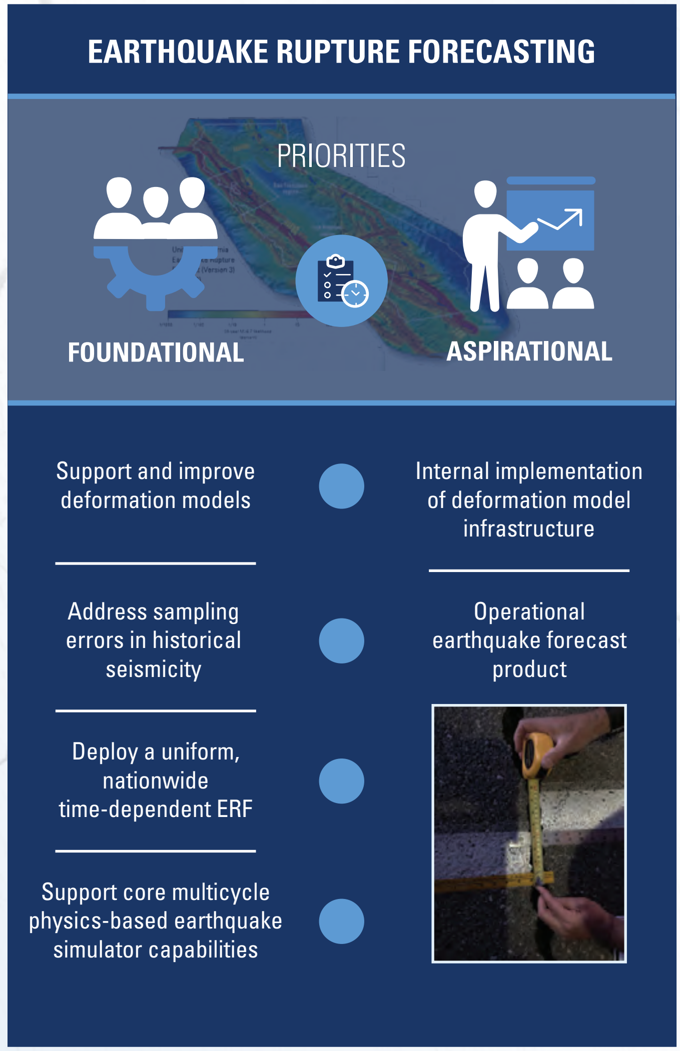


Figure 11. Earthquake rupture forecasting foundational and aspirational strategic priorities (photograph by U.S. Geological Survey; icons courtesy of LineSolution—https://stock.adobe.com/).

functional recovery as described in a 2021 FEMA publication (Federal Emergency Management Agency and National Institute of Standards, 2021). Such ERFs could not only represent elastic rebound and spatiotemporal clustering effects but also swarms and induced seismicity. In addition to their use in risk decision making, these ERFs would be useful scientifically by addressing topics like the effect of sampling errors in historical seismicity. A **foundational** priority is for the EHP to develop a uniform, nationwide, time-dependent ERF. This is being incorporated into current work plans. An **aspirational** priority is the development and deployment a nationwide OEF product, which would provide automated real-time information on earthquake probabilities nationwide. Although the resources required for such deployment would be significant, likely to require sustained programmatic investment of millions of dollars, public messaging could build off the infrastructure currently being deployed for OAF. Before substantially investing in an operational system, EHP would need to undertake a benefit-cost analysis.

Support Core Capability with Respect to Multicycle Physics-Based Earthquake Simulators.—Current ERFs make use of inferences made from multicycle physics-based earthquake simulators, and future improvements will rely on them even more. However, the USGS currently has no internal capability with respect to such models, and support for those developed and maintained externally is unstable. This has implications with respect to reproducibility of elements within our current ERFs, and it is not ideal with respect to accelerating future improvements. A **foundational** priority is to direct ERF research to support models that are currently influencing the NSHM.

Earthquake Source Processes

Earthquake source processes (ESP; fig. 12) refer to research involving field, laboratory, data analysis, and modeling investigations of earthquake occurrence and the underlying physics. This includes rapid and high-resolution source characterization of natural and induced earthquakes, the physics of rupture initiation and propagation, geologic and hydrologic controls on earthquake failure, and deformation of the fault system over the seismic cycle. At the short time scale, earthquake source models provide higher order source properties such as stress drop and rupture directivity, which inform GMMs. At geologic time scales, geophysical models of active faults and the surrounding crust provide invaluable information on long-term fault-slip rates, frictional properties, and statistical measures of earthquake occurrence, which in turn, inform ERFs and derived products such as the NSHM, as well as other products such as OAF and information provided to industry and regulators of induced seismicity.

Characterizing and Modeling Earthquake Rupture.—EHP partners and the public rely on the USGS for timely and high-quality information about recent earthquakes. A **foundational** priority is for the EHP to continue to rapidly and accurately characterize the ruptures of significant earthquakes. The EHP plans to better integrate seismic and geodetic data, aftershock locations, surface ruptures, and other observations to image the three-dimensional fault geometry, spatial slip distribution, and time history of slip. The EHP plans to develop and apply methods to estimate the uncertainty of these models. The EHP plans to continue to develop, validate, and apply state-of-the-art physics-based numerical models of these earthquake ruptures, including earthquake nucleation, dynamic rupture propagation, and arrest. Rapid results provide situational awareness during earthquake response, and detailed study at high resolution advances our knowledge of earthquake and ground-motion processes.

Advancing Models of Earthquake Physics.—Current earthquake forecast products, including the NSHM and OAF, mainly rely on empirical statistical models of earthquake occurrence. The next generation of these products can be improved through the use of physical models, which is a **foundational** priority for the program. The EHP continues to use high-resolution source characterization, laboratory rock mechanics observations, analyses of samples obtained from the Earth's surface and deep fault-zone drilling, and computational modeling to advance our physical models of earthquake occurrence. The EHP plans to pursue new and refined fault constitutive laws, improved understanding of their relation to fault zone properties and fluids, and characterization of their evolution through the earthquake cycle. The EHP plans to quantify the fault and rock properties and the hydraulic conditions that allow or prevent induced earthquakes and aseismic slip from occurring. Detailed site studies, including sample collection and laboratory analysis and testing, can improve our process-based understanding of how ruptures reach Earth's surface and distribute deformation.

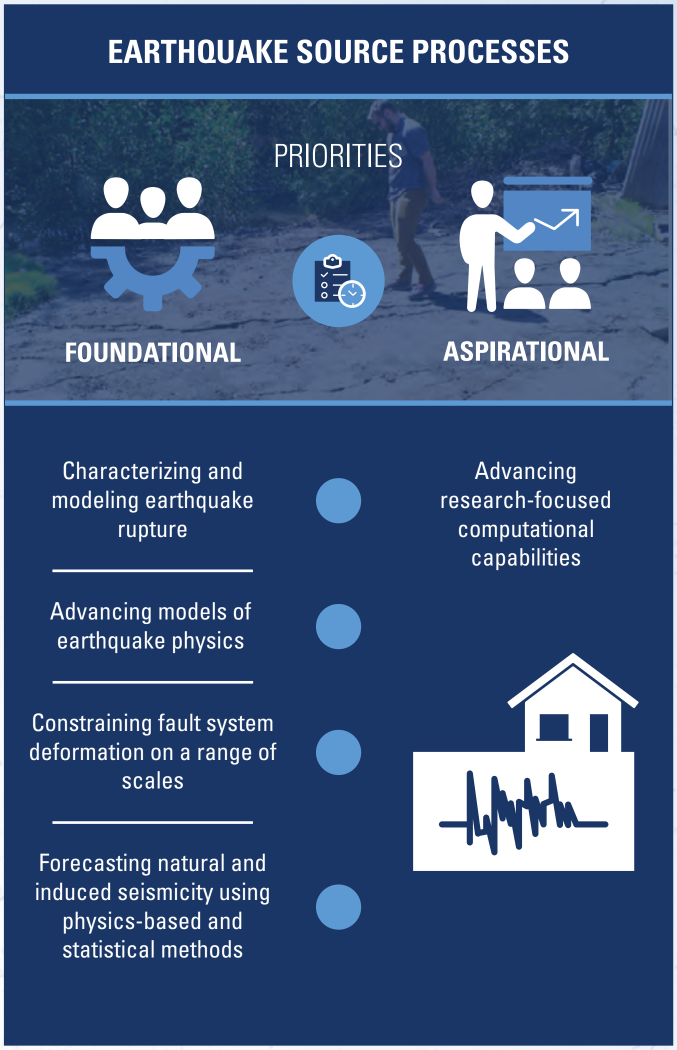


Figure 12. Foundational and aspirational strategic priorities for earthquake source processes (icons courtesy of LineSolution and ronnarid—https://stock.adobe.com/).

Application of these techniques to areas of induced seismicity offers a unique opportunity in that the geologic and physical conditions at depth are often better known than in areas of natural seismicity. Better understanding of earthquake physics can be used to develop, validate, and apply improved physics-based numerical models of multiple processes, including dynamic rupture propagation, afterslip, aseismic slip, and earthquake stress triggering. More funding would be necessary to support in situ field studies that would help to address similar questions.

Constraining Fault System Deformation on a Range of Scales.—Estimates of the frequency, slip characteristics, fault geometries, and magnitudes of potentially damaging earthquakes on the network of about 2,000 known active faults in the United States provide foundational inputs to earthquake forecasts. Primary constraints on these estimates come through geologic and geophysical field and monitoring studies of fault system behavior. It is a **foundational** priority to continue to use a variety of techniques to observe the spectrum of spatial and temporal scales of fault system deformation, including strain accumulation in the interseismic period, coseismic and aseismic slip, and postseismic slip and deformation.

Geologic and geomorphic studies characterize the near-surface geometry of the fault system and allow us to infer the fault geometry at depth. New enhanced catalogs of earthquake locations and source properties can illuminate active fault structures at depth in higher resolution than previously possible. Uncertainty can be characterized through quantitative uncertainty in fault orientation and through alternative geometric interpretations using geologic and geophysical data. Geologic, geomorphic, and geochronological studies also extend records of individual earthquakes into the past. These observations can be used to improve understanding and characterization of fault segmentation, multifault ruptures, earthquake scaling relations, and spatial and temporal slip rate variability.

Geodetic data can improve maps of present-day crustal deformation across the fault system, including vertical deformation, to better constrain fault slip rates and to better characterize regions of distributed tectonic deformation. Geologic data can be gathered to quantify fault slip rates, cumulative vertical motions, and secondary faulting over late Quaternary timescales. The EHP plans to work to better understand and characterize fault creep, afterslip, and strain transients including postseismic transients from historic ruptures, as well as how these processes affect the loading of the fault system. The relationship between fluid injection and aseismic deformation can be explored in areas of induced seismicity.

Forecasting Natural and Induced Seismicity Using Physics-Based and Statistical Methods.—Earthquake forecasts can benefit society by providing situational awareness and supporting decision making. For induced earthquakes, these forecasts can inform changes to operations to reduce earthquake risk. In parallel to efforts within ERF, the ESP subcommittee plans to continue developing physical and statistical models of time-dependent earthquake processes to support forecasting on time scales of days to years. A **foundational** priority is to extend the existing statistical framework used in OAF to support research models of induced seismicity from wastewater injection, as well as models of natural and induced earthquake swarms. A key goal will be to develop and test physics-based methods of earthquake forecasting (for example, static, dynamic, viscoelastic, and poroelastic stress-transfer models) using results from observational, laboratory, and modeling studies of earthquake occurrence. Additional resources would be necessary to

Photograph showing U.S. Geological Survey scientist observing damage in Türkiye triggered by the February 2023 Türkiye/Syria earthquake sequence, taken June 2023 by Nadine Reitman, U.S. Geological Survey.

further develop physics-based forecasts for geologic carbon sequestration and geothermal energy production. These products would be highly valuable for hazard modeling and also useful for the regulatory community.

Advancing Research-Focused Computational Capabilities.—Technological advances have led to increasingly large observational datasets, as well as larger Earth-system models. For example, seismic data density is increasing with deployment of low-cost sensors, geodetic observations are increasing with high-rate GNSS data and new satellite-based platforms, and earthquake geology is increasingly using large, high-resolution datasets of light detection and ranging (known as lidar) topography. As discussed in the "ShakeAlert" section of the science strategy, DAS also holds promise for future approaches to earthquake monitoring and requires more research, including into how to leverage and store the massive quantities of data these systems generate. To effectively use these various high-density datasets, the USGS would increasingly need to rely on machine learning and other high-performance computing techniques. An **aspirational** priority is increased investment in computational resources, including investment in more research-focused staff with computer science expertise.

Ground Motion

Ground motions are the key factor that link the occurrence of earthquakes to societal consequences. As such, GMMs are a fundamental component of earthquake hazard products, including long-term hazard and risk assessments and real-time earthquake products like ShakeMap, ShakeAlert, PAGER, and Ground Failure, which are often developed or operationalized outside of, but in strong coordination with, the ground-motion research topic. Traditionally, ground-motion research falls into two categories: empirical approaches and physics-based simulations. Until recently, USGS hazard products have primarily relied on the empirical approach. Empirical models and methods need to be improved, and simulated GMMs require continued development validation. To do so, it is necessary to address basic questions such as what is the nature and source of high- and low-frequency ground motion, and how do geologic structures affect seismic wave propagation and attenuation? Research efforts could consider how to forecast the distribution of ground motions more accurately for different earthquake hazards products and maintain consistent model selection criteria across products. More detailed understanding is needed of what ground-motion features lead to damage in structures and how those features can be better predicted. Finally, continued research topics include understanding what controls the natural variability of ground motions, how to separate and model different components of variability and uncertainty, and how to build and implement the newest GMMs that capture this natural variability. Addressing these topics leads to the following strategic priorities (fig. 13).

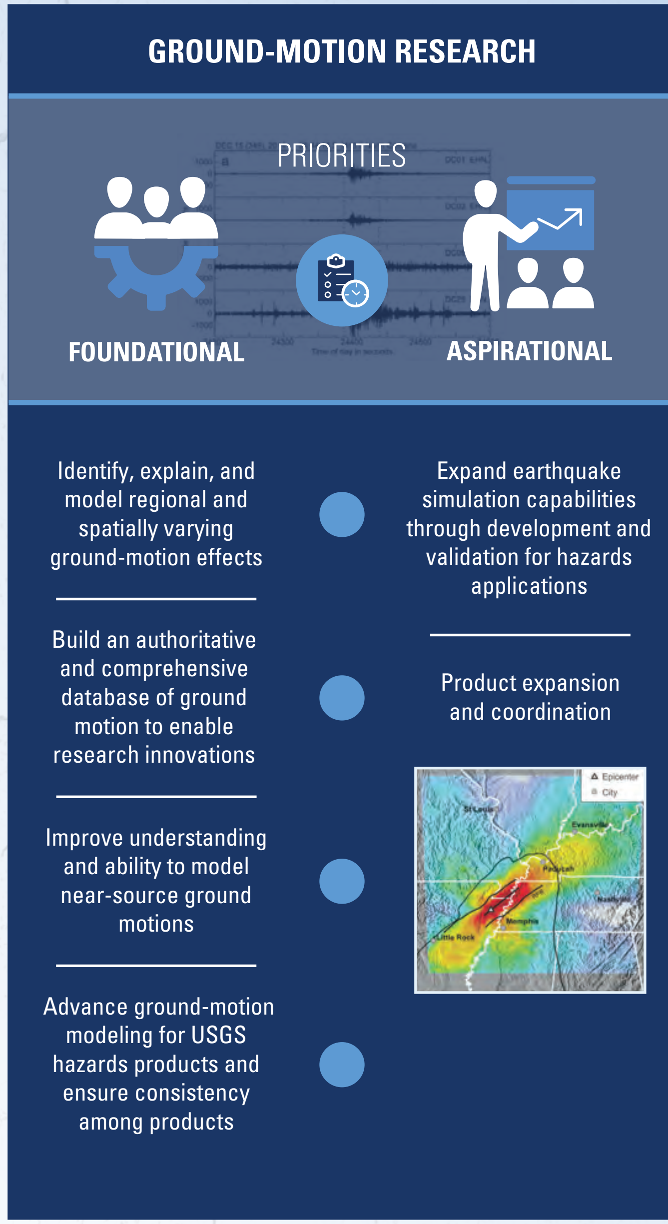


Figure 13. Ground motion research foundational and aspirational strategic priorities (map image courtesy of U.S. Geological Survey; icons courtesy of LineSolution—https://stock.adobe.com/). [USGS, U.S. Geological Survey]

Identify, Explain, and Model Regional and Spatially Varying Ground-Motion Effects.—Current and traditional empirical GMMs harness large amounts of data by assuming that similar tectonic regions have the same spatially invariant attenuation features; however, this is rarely the case and leads to large uncertainty and variability. More data facilitate more accurate and precise GMMs for these source-, path-, and site-specific situations. A **foundational** priority is to implement state-of-the-art models (known as spatially varying, source-, path- and site-specific, or "nonergodic," models) in a common framework. Additionally, efforts are planned to develop new spatially varying GMMs that meet the needs of the USGS, including expanding internal expertise to analyze and model ground motions. To do so, it will be necessary to coordinate with external groups and programs for improved and collaborative GMM development and to expand community velocity model coverage to new regions.

Build an Authoritative and Comprehensive Database of Ground Motion to Enable Research Innovations.—Continual improvement of empirical GMMs requires the curation of a database of observed ground motions, as earthquakes occur and seismic networks expand, in a consistent and easy-to-access format. A **foundational** priority is to compile and maintain a U.S.-wide database of processed ground motions, waveform metrics, and site parameters for ground-motion prediction. Specifically, this requires (1) new ground-motion data routinely and automatically updated as earthquakes occur with waveforms and engineering metrics and (2) a comprehensive, living database of existing site characterization parameters. Key site parameters include physically measurable and empirically estimated parameters that correlate with how ground motions are locally amplified or attenuated at a recording station and which are a critical component to ground-motion modeling and interpretation. Focus can also be on novel ways to characterize basin structure and models for predicting spatially varying basin amplification. It is important to document both traditional parameters in addition to new and emerging descriptors that hold promise to vastly improve predictive capability, such as the dominant site frequency and site attenuation. Continuing to collect new site- and basin-characterization data both in situ and from recordings of earthquakes can help to continually improve this database.

Improve Understanding of Near-Source Ground Motions.—Outstanding issues in ground-motion modeling include understanding the relative contributions of high-frequency versus low-frequency radiation of seismic waves within a single earthquake and the ability to model that radiation for use in applications such as earthquake simulations. Improving our understanding of parameters such as stress drop, distributed slip, directivity, radiation pattern, and asperity locations and improving our ability to include these parameters in GMMs through more complex distance- or source-characterization metrics are **foundational** priorities. Specifically, considerations include the spatial variability and repeatability of these source parameters as predictive inputs to GMMs and careful methods for isolating and modeling these near-earthquake source effects separately from site and path effects.

Advance Ground-Motion Modeling for USGS Hazards Products and Ensure Consistency Among Products.—Many USGS products, such as ShakeMap, the NSHM and ShakeAlert, use empirical GMMs as a key component, yet GMM consistency among the products is not always achieved, yielding different final interpretations for the same earthquake. A **foundational** priority is to evaluate and implement approaches to ensure easier implementation of consistent models among products and for transitioning between tectonic regimes. Developing a framework can help to ensure consistency of GMM selection criteria and treatment of uncertainty across EHP products and to make the GMMs more broadly accessible and useful for both internal and external researchers.

Expand Earthquake Simulation Capabilities Through Development and Validation for Hazards Applications.—Empirical GMMs are limited because they are based on a finite set of observations, and therefore, they are less constrained for certain settings where observations are sparse, such as near-source behavior for large earthquakes. Physics-based ground-motion simulations offer a solution to filling in that gap, thereby enabling extrapolation to new situations. Addressing how well current ground-motion simulations reproduce ground-motion observations and models, and building response, is an **aspirational** priority. Work could consider the use of dynamic rupture simulations to better constrain near-field ground-motion scaling (for example, with magnitude and distance), complex path and site scaling with different velocity structures, and what simulation parameters might be supported and better constrained by complementary research efforts (for example, the effects of stress heterogeneity or rupture direction).

Product Expansion and Coordination.—There is broad community demand for additional earthquake ground-motion-related products, such as rapid assessment of earthquake GMMs and specific parameters for response; short-term hazard and risk, updated in near-real-time (aligned with ERF and HIR); or on-the-fly development of source-path site-specific models during an ongoing earthquake sequence. For example, there is a need to provide information in support of earthquake response at more spectral periods of ground motion, with different types of intensity metrics, and using simple comparisons of recorded data to models. In collaboration with other coordination areas, many of these ideas can be met by expanding existing products or strengthening the linkage between ground-motion modeling and near-real-time products (such as OAF, ShakeMap, and ShakeAlert) to customize GMMs for specific needs or earthquakes. A similar need is present for the NSHM and to achieve consistency in the types of information that is presented across products. The scale of this effort would require additional funding, and as such, this is an **aspirational** priority.

View of Global Seismographic Network station PTCN on Pitcairn Island, December 10, 2014. Photograph by Kyle Persefield, Honeywell Technical Service, Inc., under contract to the U.S. Geological Survey.

Hazard, Impacts, and Risk

Hazard, impacts, and risk (HIR) refers to research and development related to probabilistic forecasting, scenario- and event-specific models of earthquake ground shaking (including the NSHM), of secondary hazards (such as the Ground Failure product), and of earthquake impacts (such as PAGER). It also refers to efforts undertaken toward seismic risk reduction by considering building codes and other risk-reduction strategies, with a focus on applied research, execution, and partnership. The resulting key products (for example, NSHM, ShakeMap, and PAGER) integrate the research and development of the three topics listed previously (ERF, ESP, and ground motion research), and propagate the uncertainties quantified there, in ever-improving ways.

The order of the five foundational priorities (fig. 14) is from ground shaking (hazard), to impacts (risk), and then to risk reduction, not order of importance. The additional two aspirational priorities build on these foundations but would require additional resources.

Near-Real-Time and Scenario Ground-Shaking Hazard.—ShakeMap is an EHP product for emergency management and preparedness activities that is continuously being improved. Although it currently uses GMMs based on generalized tectonic conditions, ShakeMap should be updated routinely to include constraints from simulations and from previously observed local ground motions (that is, “nonergodic” GMMs). These constraints are highly active topics of ground-motion research, and they show promise to significantly improve the accuracy of the near-real-time products and earthquake scenarios, as well as the NSHM. Achieving this next ShakeMap update entails an expansion of functionality that requires significant refocusing of research and support staff in relation to ground-motion expertise and software development. The success of this **foundational** priority requires collaborative efforts across the near-real-time and NSHM ground-motion modeling groups and increased efficiency in software development and maintenance. This work overlaps with the first priority in the “Ground Motion” section (to identify, explain, and model regional and spatially varying ground-motion effects).

Ground-Failure Hazards.—The USGS Ground Failure product is a recent and very important addition to the near-real-time EHP product suite. It provides critical information regarding secondary hazards resulting from recent earthquake shaking. The Ground Failure product can be improved by integrating regionally available information. For example, California has detailed surface geology and a large database of geotechnical surveys. This valuable information is not yet used by the ground failure models, and updating those models will require research to develop reliable and practical methods for combining models, as well as code development and maintenance. In addition to the current near-real-time and scenario Ground Failure product, this **foundational** research and development priority could also support aspirational efforts like the integration of probabilistic landslide and liquefaction models with the NSHM (that is, probabilistic liquefaction/landslide hazard analysis). Continuing to improve the Ground Failure product requires ongoing collaboration, both internally and externally, of the critical mass of EHP staff researchers who have expertise in liquefaction, landslides, and statistics.

Near-Real-Time and Scenario Impacts.—The USGS NEIC has been at the forefront in not only locating and reporting on global earthquakes and shaking but also providing rapid estimates of potential impacts in terms of damage, fatalities, and economic losses through the PAGER and ShakeCast products. Those same tools have also been used in planning and preparedness, for example by FEMA in their national-level exercises that practice responding to impacts from scenario earthquakes. Given the global scope

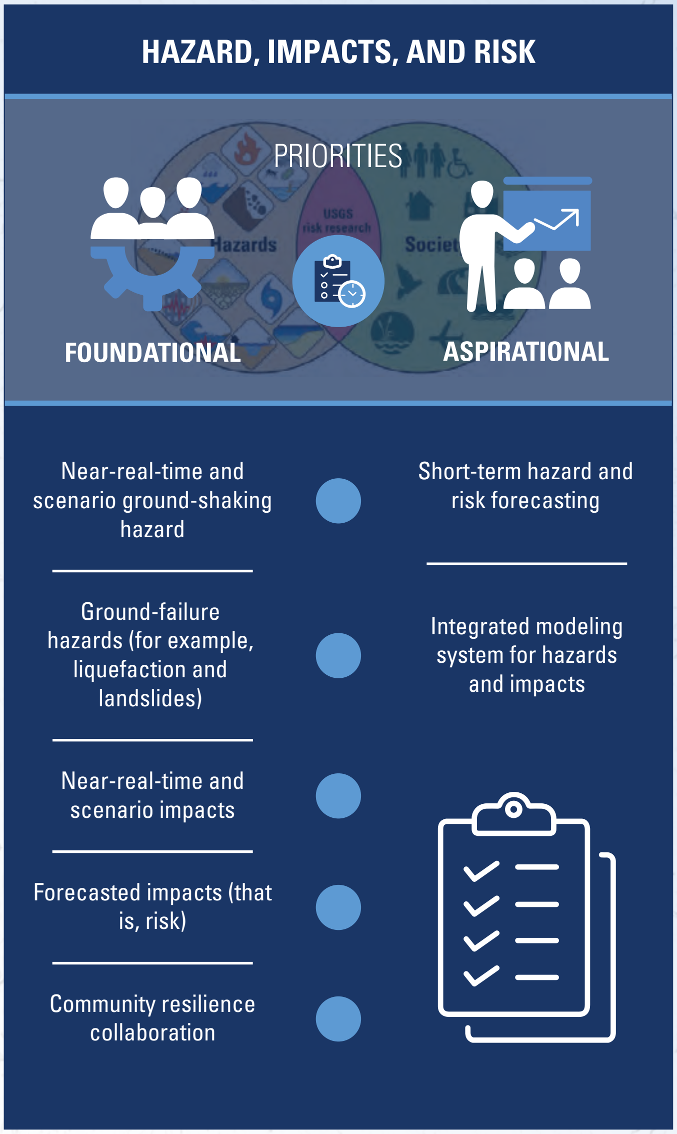
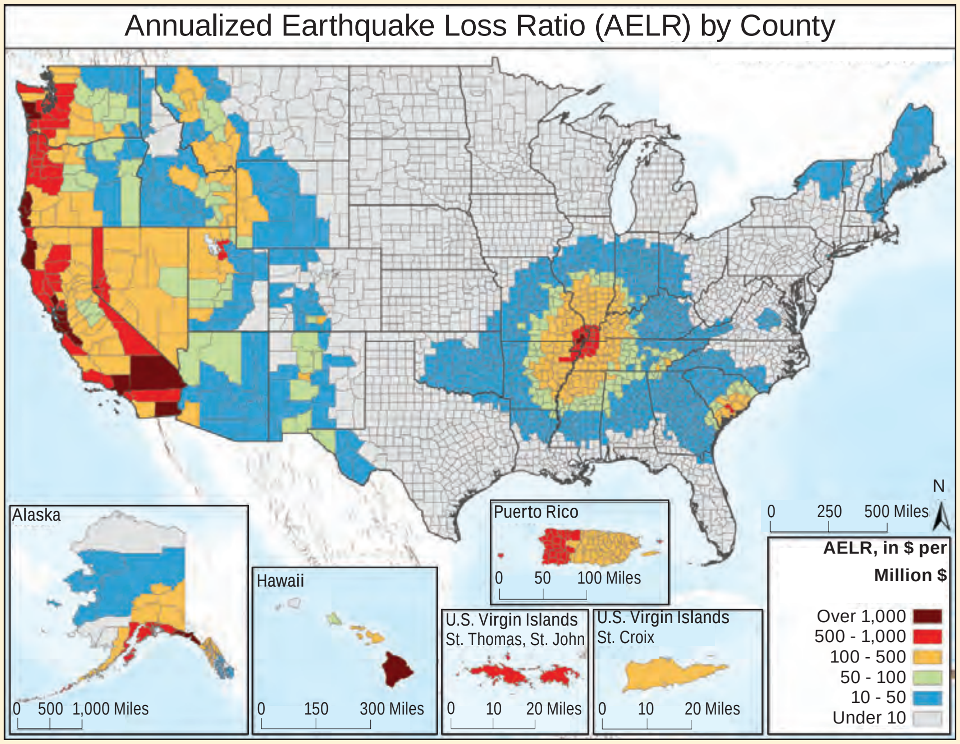


Figure 14. Hazard, impacts, and risk foundational and aspirational strategic priorities (icons courtesy of LineSolution—https://stock.adobe.com/).

Annualized Earthquake Loss Ratio in the United States and its Territories

Annualized earthquake loss ratios are shown by county in the map, representing a measure of relative earthquake risk that is calculated by combining earthquake hazard and vulnerability/risk information, normalized by the total exposed value of all building assets within each jurisdiction. Thus, if one compared two counties with similar per-year earthquake losses, the county with smaller building asset exposure value would have higher annualized earthquake loss ratios. The map helps to highlight risk across more rural counties.

This map was published as part of Federal Emergency Management Agency publication P-366, "Hazus Estimated Annualized Earthquake Losses for the United States" (Jaiswal and others, 2023). The study found that earthquake risk—currently $14.7 billion per year—is a national issue. It is increasing significantly given rising home prices, economic growth, and the nature of underlying earthquake hazard faced by both new and existing buildings. Although new construction follows modern seismic codes and benefits from the latest science and earthquake engineering research, older and existing vulnerable buildings bear much of the underlying risk. In addition to safer new construction, more attention could help to improve research on earthquake hazard and risk that is targeted at identifying and cost-effectively retrofitting existing vulnerable structures.



Base map from Esri, HERE, Garmin, Food and Agriculture Organization of the United Nations, National Oceanic and Atmospheric Administration, U.S. Geological Survey, National Park Service, and CGIAR

Annualized earthquake loss ratios by county in the United States, which represent a measure of relative earthquake risk that is calculated by combining earthquake hazard and vulnerability/risk information, normalized by the total exposed value of all building assets within each jurisdiction (modified from Jaiswal and others [2023]).

and complexity in modeling earthquake impacts, PAGER and ShakeCast require constant enhancement and updating to retain full functionality and capabilities, incorporating the latest science, observations, and state-of-the-art engineering research. These updates include incorporating ShakeMap uncertainties and observational constraints, and incorporating remotely sensed data/imagery and structural instrumentation, in order to make PAGER and ShakeCast accurate and adaptable for practical needs. Software development, modeling enhancements and broad user support for both PAGER and ShakeCast remain **foundational** priorities. EHP could also explore more sustainable models of reimbursable funding to support products like ShakeCast, given the diversity of customers and enduring service need in sectors such as transportation. Although these priorities might require initial investment, they are potentially self-sustainable in the medium to long term.

Forecasted Impacts.—Historically the USGS NSHM products have forecasted only ground shaking, which typically gets externally integrated into a variety of risk applications that forecast earthquake impacts, for example, to calculate annualized earthquake losses (Jaiswal and others, 2023; see feature box on annualized earthquake loss ratios), earthquake insurance, and seismic evaluation of infrastructure. In recent years, USGS civil engineers have engaged in seismic risk assessments of buildings and critical infrastructure (for example, highway bridges, gas transmission pipelines, and dams [Kwong and Jaiswal, 2023]), in collaboration with FEMA, the Federal Highway Administration, the California Department of Transportation, the U.S. Army Corps of Engineers (Heppermann and Luco, 2020), and other partners. These interactions improve and increase the usefulness of USGS hazard assessments, and they directly inform risk-reduction decisions, for example, by developing web and software tools, integrating both shaking and ground failure impacts on infrastructure, and accounting for spatiotemporal changes in hazard, exposure, and vulnerability/fragility. Such efforts involve continued research and stakeholder engagement, in coordination with the USGS Risk Research and Applications Community of Practice (Risk COP). Continuing to collaborate with external partners on seismic risk is a **foundational** priority.

Community Resilience Collaboration.—Since the early 1990s, the EHP has closely collaborated with risk-reduction decision makers to improve both the NSHM and building codes for the Nation's infrastructure. The scope of this research and development has grown substantially over the years, most recently to accommodate the call for community resilience (more than just life safety) in the 2018 reauthorization of NEHRP. In addition to coproduction of the NSHM and building codes, community resilience necessitates new risk-reduction collaborations between civil engineers and near-real-time USGS products such as OAF, ShakeMap, structural health monitoring, and ShakeAlert. Example applications of such research and development include improvements to red/yellow/green tagging of buildings after earthquakes and protective actions within transportation and lifeline systems. These community resilience collaborations, a **foundational** priority for HIR, require increased coordination between the NSHM and near-real-time USGS products, as well as between USGS and external civil engineers (such as those at NIST and FEMA or those funded by NSF). The new collaborations also compel ever more efficient means of engaging with risk-reduction decision makers, for example, through symposia that include numerous partners simultaneously.

Short-Term Hazard and Risk Forecasting.—Since the 1970s, the EHP has conducted research to develop long-term (50-year) forecasts of earthquake ground shaking, intended for applications such as building codes, currently under the auspices of the NSHM. From 2016 to 2018, the EHP also developed 1-year forecasts that accounted for induced seismicity and could be applied in, for example, insurance decision making. Even shorter term hazard and risk forecasts were prototyped as part of the Third Uniform California Earthquake Rupture Forecast (known as UCERF3; Field and others, 2017). Primarily for earthquake-response applications, the EHP has moreover developed near-real-time products such as OAF, ShakeMap, and formerly the Short-Term Aftershock Probability (known as STEP) hazard maps. Collectively, these and future EHP products could meet the needs for near-real-time, short-term (for example, week-long) ground shaking and failure forecasts that are analogous to the current long-term NSHM, which continue to be a **foundational** priority for periodic updates and improvements. Example applications of short-term forecasts include post-earthquake decisions on evacuating buildings, lowering levels of water behind dams, and lowering levels of liquefied natural gas in storage tanks. For risk-based decision

National Seismic Hazard Model and Maps

The U.S. Geological Survey (USGS) contributes to earthquake risk mitigation strategies by developing a National Seismic Hazard Model (NSHM) and related products (for example, regional and national hazard maps) that describe the likelihood and potential effects of earthquakes nationwide, especially in the urban areas of highest risk. Federal, State, Tribal, and local government agencies, architects and engineers, insurance companies and other private businesses, land use planners, emergency response officials, and the public rely on the USGS for earthquake hazard information to refine building codes, develop land-use strategies, safeguard lifelines and critical facilities, develop emergency response plans, and take other precautionary actions to reduce losses from future earthquakes. These activities are an essential contribution to fulfilling the USGS role within the National Earthquake Hazards Reduction Program. For example, the NSHM is the basis for the seismic provisions of building codes that affect domestic construction costs, estimated at close to $2 trillion per year (U.S. Census Bureau, 2024). After the 1989 Loma Prieta earthquake, USGS work helped inform $73 to $80 billion in investments over 30 years to retrofit or replace structures to mitigate the impacts of future San Francisco Bay area earthquakes (Brocher and others, 2018).

In 2023, the Earthquake Hazards Program has concluded the work of updating the latest version of the NSHM. For the first time, the 2023 update includes a unified, comprehensive model for all 50 States. This comprehensive update was published in December 2023 (Petersen and others, 2024).

making, such applications could additionally integrate EHP data from structural instrumentation and EHP modeling of structural fragility/vulnerability to ground shaking and failure. The new research and development needed to operationalize near-real-time, short-term hazard and risk forecasts (for example, near-real-time updating of GMMs) is an **aspirational** priority that would require significant EHP investment and would also be dependent on increased collaboration between the NSHM, OAF, ShakeMap, the NSMP, and EHP civil engineers. This goal aligns with the ERF OEF priority.

Integrated Modeling System for HIR.—As methods for seismic hazard and impact modeling have grown in complexity and sophistication, the increasing level of effort needed to maintain and advance the software infrastructure that incorporates these methods is an ongoing challenge for the USGS. EHP products could better leverage related and sometimes overlapping methods as they continue to provide trusted and authoritative information. For example, ShakeMap, the NSHM (fig. 15), and ShakeAlert could codevelop a communal software library of GMMs (empirical and simulation based)—aligning with the "Ground Motion" section priority of product expansion and coordination—and ShakeCast and collaborative EHP risk assessments (for example, with FEMA) could share structural fragility/vulnerability models. A more efficient and seamlessly integrated system is an **aspirational** priority requiring long-term planning, resource management, and coordination with subject-domain experts, potentially across other NHMA programs. Successfully addressing this need is especially important because a more efficient seismic modeling infrastructure can have broad benefits for existing EHP staff, freeing up time for other research and development priorities, including those enumerated previously. This priority also aligns with an aspirational priority from the ESP section to advance research-focused computational capabilities.

Summary of Targeted Research Priorities

Several common themes align across these targeted research priorities: regionalized, or "nonergodic" GMMs; time-dependent earthquake forecasts; improved assessments of epistemic uncertainties in hazard models; improved integration of models across various EHP projects and products, including monitoring, near-real-time shaking and impact assessments, and the NSHM; and expanded computational capacity and coordination. Coupled with other priorities identified in ERF (support for physics-based simulators) and in HIR (risk forecasting), these together could be unified under the concept of an earthquake forecasting enterprise (such as in Field [2022]). Although the combination of these collective priorities into a common initiative akin to such a forecasting enterprise is aspirational, it is clear that many components are foundational to EHP and will be leading goals for the execution of USGS earthquake science over the coming decade.

It is also clear that integration across EHP research disciplines (and with other SCC areas) is necessary to execute these strategic priorities, to ensure consistency, and to eliminate redundancy. These priorities underlie a variety of flagship EHP products, including the NSHM, ShakeMap, PAGER, and OAF, and identifying common themes and uses across a variety of needs, primarily through coordination in the EHPC, will be critical to the successful execution of this science strategy. The system-level science necessitated by these common priorities will also improve our ability to update key products like the NSHM more efficiently, while also ensuring those products are based on best-available science, developed in concert with—rather than independently of—the updates themselves.

Regional Coordination

Both internally and externally, the EHP relies on regional coordinators to represent six broad geographical regions: Northern California, Southern California, the Intermountain West, the Pacific Northwest, Alaska, and the Central and Eastern United States, including Puerto Rico and the U.S. Virgin Islands. A national coordinator also represents geographically smaller domains across the Nation, including Hawai‘i and the U.S. territories of Guam, the Northern Mariana Islands, and American Samoa. These coordinator roles ensure that region-specific needs are represented in program management and execution, with the aim that an appropriate array of geographically focused program activities is retained. Responsibilities include identifying opportunities for collaboration across regions or between regionally focused projects, interfacing with State and regional partners in earthquake research and outreach, sharing findings and best practices between regions, earthquake response and coordination, and advising the program on the development of regional earthquake probability forecasts, hazard models, and risk-mitigation efforts such as fault-setback zoning (fig. 16).

Maintain Regional Coordination for NSHM.—The NSHMs are updated approximately every 6 years for the 50 States. Updates to models for the U.S. territories (Puerto Rico and the Virgin Islands, Guam and the Northern Mariana Islands, American Samoa) have been less frequent in the past but are moving to a similar regular update schedule in the future. This requires coordination with and across regions and USGS science centers, internal coordination with experts in earthquake rupture forecasting and ground-motion modeling, and external coordination with regional and topical experts who can provide new input data and research results and help facilitate NSHM improvement. These activities are supported through communication between regional coordinators and NSHM staff that facilitate working groups within each region

NATIONAL SEISMIC HAZARD MODEL

Starting in 1989, the USGS began developing a National Seismic Hazard Model to describe the likelihood and potential effects of earthquakes nationwide, especially in the urban areas with the highest level of risk. Earthquake hazard information is used by officials, engineers, and others to refine building codes, safeguard lifelines and critical facilities, and take other precautionary actions to reduce losses from future earthquakes.

$2 TRILLION

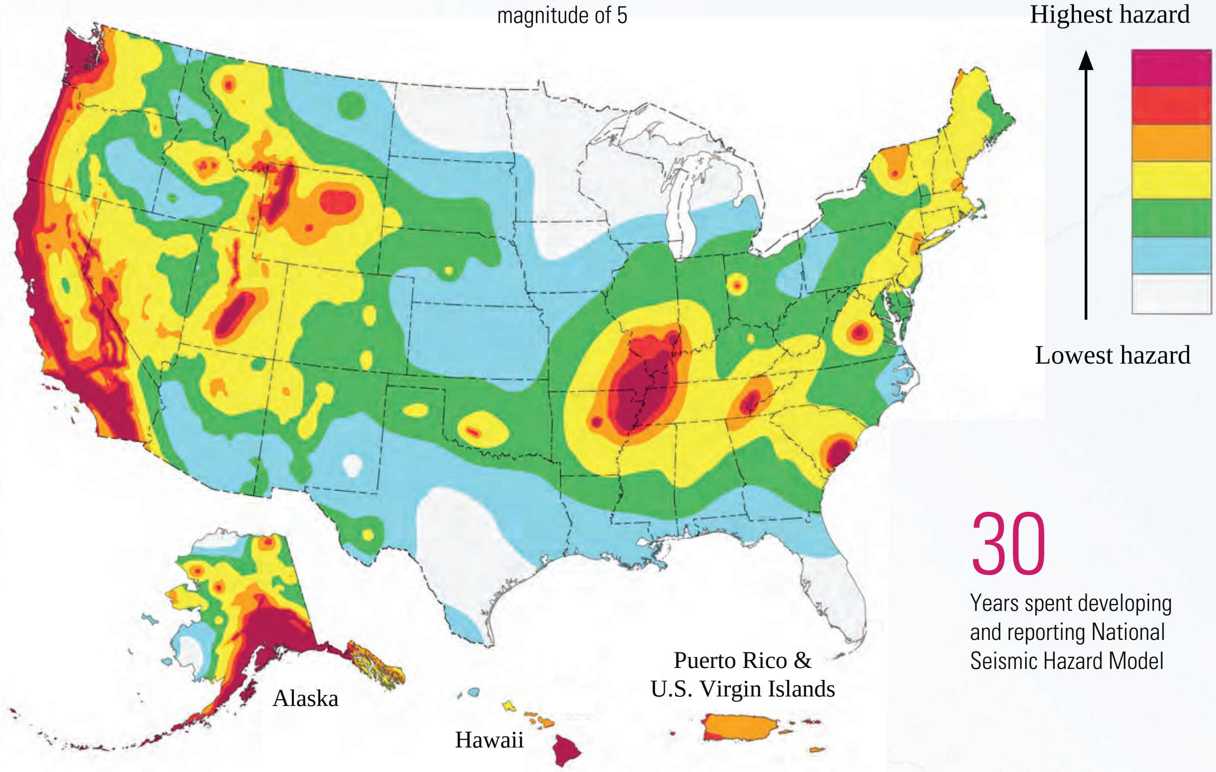
Dollars spent each year on construction of buildings that meet earthquake shaking standards

75%

Percentage of U.S. territory that has experienced earthquakes exceeding a magnitude of 5

2023

Year of the most recent National Seismic Hazard Model



30

Years spent developing and reporting National Seismic Hazard Model

$73–80 BILLION

Total dollars spent retrofitting or replacing structures to mitigate the impacts of future San Francisco Bay Area earthquakes

50

Number of States included in the most recent seismic hazard model

Figure 15. Summary of the National Seismic Hazard Model 2023 update, including key statistics developed from the model, the first 50-State model update, and the latest in 30 years of National Seismic Hazard Model research and development (map courtesy of U.S. Geological Survey).

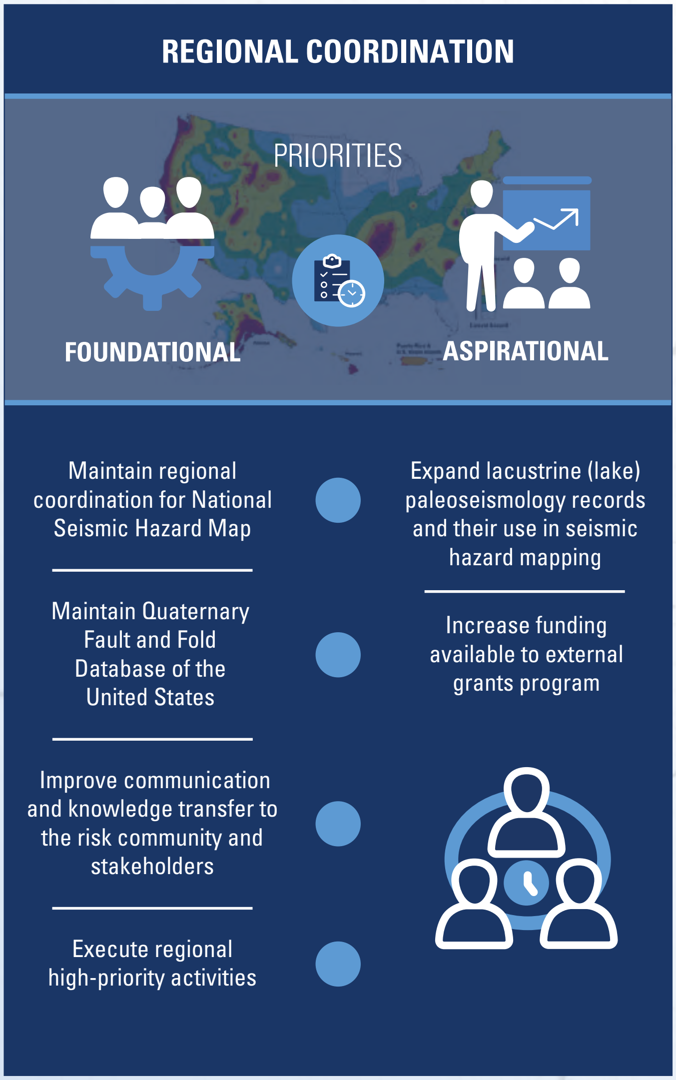


Figure 16. Regional coordination foundational and aspirational strategic priorities (icons courtesy of LineSolution—https://stock.adobe.com/).

to incorporate new data and methods and help in construction of input models. Regional coordinators serve a critical role in maintaining communication with stakeholder agencies that use and contribute to this flagship product, and thus, it is a **foundational** priority for the program.

Maintain Quaternary Fault and Fold Database of the United States—The Quaternary Fault and Fold Database (https://www.sciencebase.gov/catalog/item/589097b1e4b072a7ac0cae23), called "Q-faults" for short, is the unified, national source for active fault mapping in the United States. Each entry consists of location and rate information for faults capable of generating strong or damaging earthquakes. Q-faults receives thousands of page views per month and is used by stakeholders, scientists, and the private sector for locating and defining the framework of earthquake sources in the United States. A **foundational** regional coordination priority is to maintain and strengthen this flagship EHP product. A redirection of current information technology (IT) staff responsibilities, achieved by engagement through the EHP IPT, is needed to bring this resource to modern standards with a structure that can flexibly and efficiently incorporate and communicate new information.

Improve Communication and Knowledge Transfer to the Risk Community and Stakeholders.—Great gains in earthquake risk mitigation come from interaction with stakeholders such as State and local government agencies, private and academic organizations, major infrastructure and industrial entities domestically, and internationally through interaction with equivalent agencies. Regional coordinators serve as a communication link between EHP initiatives and products and these organizations, which may be region-specific in structure and mission. Such relationships are exercised during earthquake-response planning and are tested following major earthquakes. A **foundational** priority is to sustain these relationships and, where advantageous, strengthen communication and knowledge transfer with user groups to ensure that our science is used, adopted, and improved for risk reduction. Such engagement will also inform the EHP regarding the need for revised or new products. This priority overlaps with the "Hazard, Impacts, and Risk" section priority of risk reduction.

Execute Regional High-Priority Activities.—EHP research activities in each region are variable, reflecting diverse geologic settings including the tectonically active San Andreas Fault system, Cascadia and Alaska Subduction Zones, the Basin and Range Province, U.S. territories, and more diffuse seismicity in the Central and Eastern United States. The state of integration of research avenues in each region is similarly variable. Broadly, two categories of work are sustained by internal and external regional coordination, and their continued execution are a **foundational** priority:

- Detailed investigations of seismic hazard and risk, including time-dependent processes, with a focus on vulnerable communities and infrastructure. Examples could include (1) seismic hazard characterization in areas with far-reaching impacts such as the Sacramento-San Joaquin Delta region, areas of elevated urban seismic hazard in the western United States, and understudied regions such as the U.S. territories; (2) fault-specific and regional fault system studies through paleoseismic, geodetic, and geophysical investigations tailored to regional knowledge gaps; (3) regional testing of ground-motion predictions using intensity, strong motion records, paleoliquefaction, ground failure, and fragile geologic features; and (4) observing, quantifying, modeling, and potentially forecasting hazardous deformation processes.

- Integration and modeling of rupture processes and impacts to local communities. Prior to incorporation in the NSHM, scientific research to improve local components of seismic hazard characterization largely reflect the state of knowledge in each area. For example, the accuracy and detail of fault models, especially variable representations of geometry and connectivity, vary significantly across the United States. Velocity models are similarly diverse in detail and size due to past data collection and integration efforts. There may also be significant differences in how hazard information is translated into risk reduction at the local scale, including issues that are related to program goals outlined in the "Diversity, Equity, Inclusion, and Accessibility" section. A regional coordination priority is to continue to pursue these localized studies, which eventually are incorporated into flagship EHP products.

These efforts overlap scientifically with ground motion and ESP priorities but are focused regionally.

Expand Lacustrine (Lake) Paleoseismology Records and Their Use in Seismic Hazard Mapping.—Lake basins preserve high-fidelity records of strong ground shaking from earthquakes and are a cost-effective means to improve long-term (thousand-year) records of strong seismic shaking. Moreover, lacustrine paleoseismology is the only technique that can evaluate the frequency of strong intraslab earthquakes, and it holds significant potential for areas where the seismic sources cannot be identified through typical techniques, such as in the central and eastern United States. Although current limited-scope efforts in this emerging field are planned to continue, additional investment would be required to (1) grow EHP expertise in this emerging field, (2) develop new lacustrine paleoseismology data and tools, and (3) foster growing internal and external collaborations, for example, between the EHP and the Pacific Coastal and Marine Science Center. This is an **aspirational** priority for EHP. The program would benefit from engaging seismic hazard modelers to develop tools that integrate these and similar metrics into hazard models and test results against predictive models.

Global Monitoring

Global earthquake monitoring activities for the USGS straddle two programs: the EHP and the GSN (fig. 17). Within the USGS, the GSN program is coordinated out of the EHP office and is responsible for a network of state-of-the-art seismological and geophysical sensors connected by a telecommunications network, which in turn, serves as a multiuse scientific facility and societal resource for monitoring, research, and education.

The GSN consists of 141 globally distributed stations, 95 of which are operated by the USGS. The network is a partnership between the USGS and the NSF and is currently implemented in partnership with the EarthScope Consortium (previously called the Incorporated Institutions for Seismology, or IRIS), university consortia, and many other entities. It provides the high-quality seismic data needed for global earthquake alerts and situational-awareness products, tsunami warnings, national security (through nuclear test treaty monitoring and research), seismic hazard assessments, and earthquake loss reduction, as well as research on earthquake sources and the structure and dynamics of the Earth.

Because of its real-time data delivery, the GSN is a critical element of USGS hazard alerting activities. The GSN also supports activities of other Federal agencies, including the National Oceanic and Atmospheric Administration (NOAA) for tsunami warning, NSF for basic research, and the Department of Energy and the Department of Defense for nuclear test treaty monitoring and research. GSN stations transmit real-time data continuously to the USGS NEIC, where they are used to rapidly determine the locations, depths, magnitudes, and other parameters of earthquakes worldwide, in conjunction with data from other seismic networks. GSN data allow for the rapid determination of the location and orientation of the fault that caused the earthquake and provides an estimate of the size of the fault that ruptured during the earthquake and how much slip occurred, which are essential for modeling earthquake effects. The very broadband, low noise, high quality nature of GSN data is a critical aspect of these applications and is essential for fully characterizing the largest magnitude earthquakes, such as the devastating magnitude 9.1 2004 earthquake in Sumatra, Indonesia, and the magnitude 9.1 2011 earthquake in Tohoku, Japan. An additional important aspect of GSN activities is evaluating, developing, and advancing new technologies for seismic instrumentation, sensor installation, and seismic data acquisition and management. The following priorities outline leading goals for global seismic monitoring over the coming decade (fig. 18).

Long-Term Operations and Maintenance.—It is critical to continue the long-term maintenance and upkeep of the approximately 100 globally distributed, very broadband seismic stations supported and operated by the USGS. This multiuse state-of-the-art seismic network should continue to operate in locations that maximize global coverage while recording the entire seismic spectrum (from Earth tides to nearfield high-frequency events). Notably, the GSN is one of the few networks on the planet capable of recording long-period seismic signals with high fidelity. These signals are extremely important for understanding the rupture characteristics and size of great earthquakes. This is a **foundational** priority for the EHP and GSN.

GSN Deferred Maintenance.—In order for the GSN to continue providing state-of-the-art, high-quality seismic data, it will be necessary to improve all GSN vault sensors (and associated site infrastructure) that have not been modernized during the ongoing borehole upgrade project, currently scheduled for completion in FY 2026. Future deferred maintenance efforts will also require the development of the next generation datalogger, because the current Quanterra Q330HR will eventually become obsolete. Although aspects

GLOBAL SEISMOGRAPHIC NETWORK

Based on a partnership between the National Science Foundation and the U.S. Geological Survey (USGS), the Global Seismographic Network is a permanent digital network of state-of-the-art seismological and geophysical sensors connected by a telecommunications network that serves as a multiuse scientific facility and societal resource for monitoring, research, and education.

141
Number of globally distributed seismic sensors

95
Number of seismic sensors directly operated by USGS

365
Days a year that USGS provides rapid characterization of all significant earthquakes worldwide

67
Number of new global seismic sensors installed since 2022

88%
Percentage return rate of data from global seismic sensors

Figure 17. Summary of the Global Seismographic Network (modified map image courtesy of National Science Foundation Seismological Facility for the Advancement of Geoscience and U.S. Geological Survey).

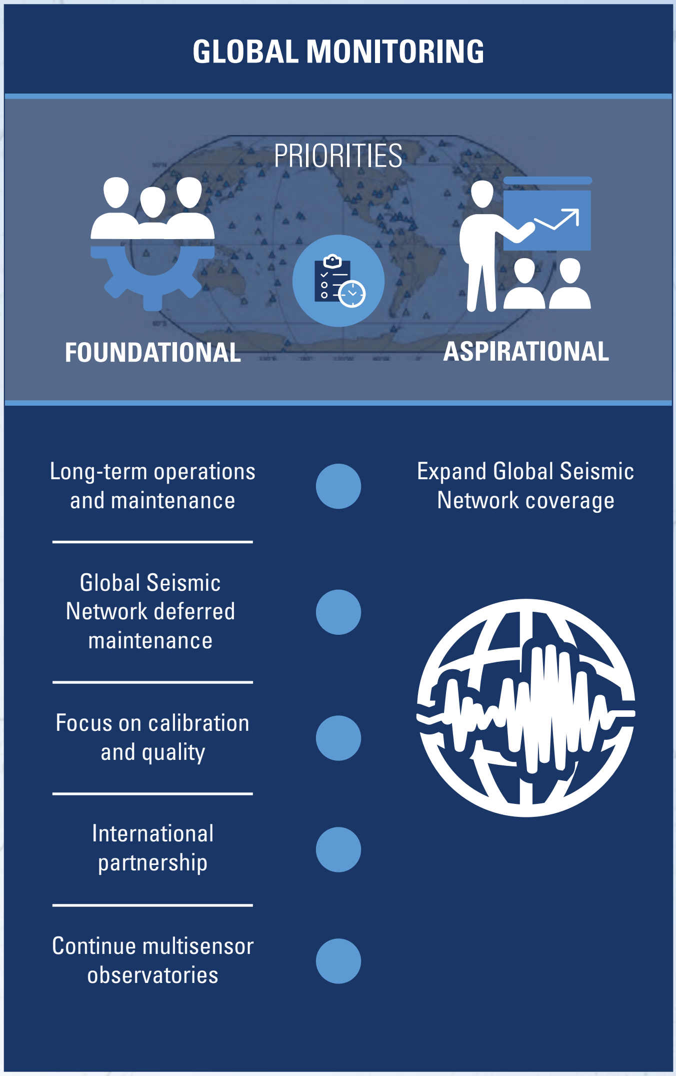


Figure 18. Global monitoring foundational and aspirational strategic priorities (icons courtesy of LineSolution and ronnarid—https://stock.adobe.com/).

of these deferred maintenance requirements are **foundational**, more funding would be required to address all issues within the next decade.

Focus on Calibration and Quality.—It is important for the GSN to further develop and apply state-of-the-art calibration and data quality control techniques to ensure the continued quality of the dataset. Quality control of the GSN includes testing for and publishing accurate amplitude response, phase response, and timing information. The GSN is often used for decadal studies that help to improve our understanding of Earth structure, inner-core rotation, anthropogenic noise, and climate change. To robustly resolve the temporal changes in these observations, accurate and precise metadata are crucial. As a **foundational** priority, the GSN should leverage the very best techniques to make this data as useful as possible to future scientists. This includes calibrating sensors to NIST's traceable standards (Anthony and others, 2018). Along with calibration, orientations and timing should ideally be an order of magnitude better than current research requires to ensure that current monitoring and research efforts are not limited by instrumentation. For example, the GSN aims to constrain amplitudes to within 1 percent whereas current attenuation tomography and source characterization amplitudes are not better than 10 percent.

International Partnership.—Improving international partnership and participation in the maintenance and upgrade of GSN stations is a **foundational** priority. Working with non-USGS station operators, instrumentation developers, and data users could allow the usefulness and uptimes of these multiuse seismic stations to be improved and maximized. Currently, as many as 65 percent of USGS GSN stations have station operators that can provide nontrivial help and station maintenance. However, as many as 25 percent of USGS GSN stations have poor or nonexistent station operation partners. Because 12 of the 20 most geographically isolated seismic stations that contribute near-real-time data for earthquake characterization to the NEIC are GSN stations, it is imperative that these stations produce high-quality data to meet the global earthquake monitoring goals of the USGS. Continually improving collaborations with local station operators can ensure continued or improved data quality from USGS GSN stations.

Continue Multisensor Observatories.—The recording of pressure, temperature, the local magnetic field (partially supported by the USGS Geomagnetism Program), and rainfall alongside multiple redundant seismic recordings make the GSN a truly multiuse network. It is a **foundational** priority to continue to maintain and operate meteorological and additional geophysical instrumentation at GSN stations. Doing so can help to ensure the long-term success of this network. Additional types of data streams (for example, strain, tilt, and absolute gravity) could be opportunistically added if funding sources are identified. Many applications are more and more reliant on additional geophysical measurements being recorded at GSN stations, including within other USGS programs such as the Geomagnetism Program, which is also housed within the NHMA.

Expand GSN Coverage and Monitoring.—An **aspirational** priority is to develop infrastructure and procedures to continue the improvement of coverage of the GSN by way of arrays and additional modernization in processing algorithms and data streams that help to improve the NEIC global monitoring mission. Improved data coverage has the potential to lower thresholds of global earthquake detection. Any new arrays would be strategically placed to complement land-based stations with minimal additional logistical costs and with an eye for improving detection and response times. This should also be executed with the continued goal of providing the very best possible data (for example, maximum uptimes and low noise levels across the entire seismic spectrum) at these additional stations.

Crosscutting Activities

Several activities span the major subcomponents of the program, and the individual seats of the SCC, and are discussed within a broader framework in this section. A summary of plan priorities spanning these various activities is as follows (fig. 19).

Communications and Outreach

Earthquake-related communication and outreach involves activities over a variety of differing timescales—both during event response and for longer term partner, public, academic, and media engagement independent of earthquake-response activities. The USGS provides critical information to decision makers through some of the most heavily trafficked websites in the Federal Government. Earthquake products form the core of EHP's science delivery strategy, and the impact of the program is largely dependent on the effectiveness of these products. Also pivotal to EHP's impact and recognition is how the program leverages communication and outreach resources to distribute and highlight these products. This is especially important today given the variety, availability, and rapid evolution of mechanisms through which we communicate. Whether via traditional websites, social media, or other tools, EHP should be well positioned to distribute information, educational resources, and related material in a corresponding variety of ways.

EHP relies on several mechanisms for effective communication. The program interfaces with the USGS Office of Communications and Publishing (OCAP) to develop high-profile news stories related to new content or highlights and produces material for associated media engagements. The program supports communication-focused staff at both ESC and GHSC who lead efforts to develop communication material for new (predominantly center-specific) products, publications, and highlights, including material for distribution on USGS social media channels. EHP also benefits from science staff who volunteer time to support education and outreach efforts (public lectures, presentations at schools and museums, facilities tours, and so on) and who maintain active social media engagement, for example through X (formerly Twitter) channels for the EHP (@USGS_Quakes) and ShakeAlert (@USGS_ShakeAlert).

Given the large and growing number of ways in which EHP engages in communication and outreach, the need to maintain an active presence on social media, and the desire to provide content and products to end-users in new and creative ways, an **aspirational** priority of the program is to expand communications and outreach focused staff, including the recruitment of at least one more communications specialist to oversee and coordinate the program's myriad engagement mechanisms.

Figure 19. Crosscutting foundational and aspirational strategic priorities (icons courtesy of LineSolution—https://stock.adobe.com/). [NOAA, National Oceanic and Atmospheric Administration; IT, information technology; DEIA, diversity, equity, inclusion, and accessibility; EHP, Earthquake Hazards Program]

Communications During Earthquake Response

The fundamental goal of the EHP for post-earthquake communications is to serve public interests by ensuring the safety, security, and economic well-being of the Nation. We can support this goal with effective communication—rapid, organized, reliable communication of authoritative knowledge serves to address community concerns, is a teachable moment for disaster education, and helps to promote effective mitigation—a bridge to the longer term communication mechanisms discussed previously.

An organized and staged approach to media engagement in a post-earthquake environment is not always immediately possible and should not be the driving factor governing such media interactions. After an impactful earthquake, our audience expects to receive information quickly, and EHP needs to position itself to be the authoritative source of information immediately—otherwise other groups will respond before EHP and for EHP. The EHP can work together with the OCAP to pre-position message content. A list of spokespeople who can be relied on to effectively deliver that messaging can be developed while other event facts are gathered, more detailed talking points are created, and a comprehensive product suite is developed.

The EHP, and our USGS hazard programs across the NHMA, are the face of USGS—and of science in general—after major hazard events. For significant events, particularly domestic ones, response needs last for weeks after the event in question, creating a high demand both on scientists and on OCAP coordination activities. It is critical that the EHP establishes clear structures and guidelines that support response activities, such that the program can nimbly and rapidly respond to a variety of needs. A **foundational** priority of this plan is for EHP leadership to work with the OCAP on the development of an appropriate earthquake-response plan as a component of broader communication and outreach strategies.

Enhanced Communications Products

Venues for effective communication of earthquake research and information are evolving and expanding. Social media, text messages, and email notifications are currently preferred methods for distributing links to well-established EHP earthquake information (for example, recent earthquakes and impact assessments such as PAGER), supplemented by recently published related research (such as updates to the NSHM). In addition, the “News” section of the EHP website is used to highlight a variety of new research or product releases.

These traditional tools for disseminating earthquake information have recently been supplemented with new products built on the ArcGIS StoryMap framework. Following recent significant domestic or international earthquakes, EHP staff have successfully used these StoryMaps to provide expanded information on earthquake sequences using a format that allows the inclusion of more detailed and dynamic information on source modeling (for example, finite fault models and areal distribution of aftershocks), observations of ground deformation, and seismotectonic framework (Schmitt and others, 2024). StoryMaps are an effective way to combine high-quality interactive maps, figures, and animations, as well as links to existing EHP products that better illustrate earthquake processes and associated geology, tectonics, and seismic hazard information. StoryMaps also provide the earthquake science community, media, and the public better insights into the underlying processes used in making critical EHP products (such as the NSHM). StoryMaps also allow us to provide more comprehensive background information on the tectonic setting of important seismically active regions (for example, the Stern and others [2021] StoryMap showing the east margin of the Australian Plate). Such background StoryMaps can be produced during quieter periods between major earthquake responses, and they are useful pre-positioned content that can be promoted by the EHP and OCAP during earthquake response. An **aspirational** priority is for the EHP to expedite the development of sequence-centric products and expand the use of StoryMaps (and similar interactive communications mechanisms that may be developed in future) to better communicate highly visible earthquake sequences, their seismotectonic context, and associated seismic hazards.

Photograph showing U.S. Geological Survey researchers hike across Henrys Lake, Idaho, to a sediment core extraction location on March 30, 2023. Photograph by Sylvia Nicovich, U.S. Geological Survey.

Earthquake-Response Coordination

The Earthquake Hazards Reduction Act calls for the investigation of significant domestic and international earthquakes to learn lessons that can help reduce future earthquake losses in the United States. The act also specifically directs the USGS to organize post-earthquake investigations to study the implications of earthquakes in the responsibility areas of each of the four NEHRP agencies and to use expertise of other Federal agencies, State partners, nongovernmental organizations, and private contractors. Thus, the USGS is the lead NEHRP agency for activating and coordinating NEHRP-related post-earthquake investigations. Guidance in this role comes from USGS Circular 1242, “The Plan to Coordinate NEHRP Post-Earthquake Investigations” (Holzer and others, 2003), which describes the coordination and responsibilities associated with earthquake disaster reconnaissance as discharged by multiple government, professional, and research organizations. Circular 1242 (Holzer and others, 2003) has been revised recently, with the update nearing publication. The USGS implemented elements of the revised plan following the February 2023 earthquakes in Türkiye.

Major earthquakes also provide critical information on earthquake processes, ground shaking, and the performance of the built and socioeconomic environments. Post-earthquake investigations should be coordinated to maximize learning and to translate lessons quickly and effectively into practices that mitigate the impacts of future earthquakes. Experience has demonstrated that well-executed scientific and engineering investigations can substantially further the achievement of the goals of improved societal preparedness, enhanced emergency response and recovery, better characterization of earthquake hazards, improved understanding of the physical and societal impacts of earthquakes, and the provision of authoritative information to affected communities.

Because of the infrequency of large, damaging earthquakes, and the many investigators who can be expected to conduct field studies after earthquakes, post-event investigations benefit from close coordination in order to maximize the ability to improve future mitigation efforts. The USGS must stand ready to respond quickly following domestic or international earthquakes that may strike at any time and in any place. This requires that investigation plans and procedures be documented, shared within the agency and with potential partners, and exercised in order to promote working knowledge of procedures, roles and relationships. Furthermore, investigation results must be disseminated broadly in order to transmit findings and lessons learned, and results should be published or otherwise archived. The following are associated **foundational** priorities:

- Maintain, advance, and implement procedures and policies for post-earthquake investigations and data acquisition management, following USGS Circular 1242 (Holzer and others, 2003) and its updates.
- Develop and conduct exercises and training sessions to test and promote working knowledge of procedures, roles, and relationships among NEHRP agencies, partners, and stakeholders.
- Working with NEHRP partners and others, translate results from post-earthquake investigations into approaches for improved resilience.

Earthquake Disaster Assistance Team Coordination

The U.S. Agency for International Development Bureau for Humanitarian Assistance (BHA) is responsible for leading and coordinating the U.S. Government’s response to disasters overseas. The goals of the NHMA’s cooperative work with the BHA are to (1) conduct and deliver science and information to reduce losses and risks from natural hazards, including earthquakes, landslides, and related hazards, (2) leverage international work to advance domestic science priorities, and (3) foster and grow productive relationships with international scientific counterparts. Although the focus of the EHP is predominantly domestic, defined by legislation establishing NEHRP, it also supports international earthquake monitoring and advancement of the understanding of hazard and risk. USGS scientists routinely respond to requests for assistance in foreign countries through the BHA. The EHP supports the BHA’s response to disasters by providing situational awareness for recent and ongoing earthquakes to international counterparts through rapid event characterization products, impact and loss assessments, and the collection, examination, and interpretation of remote data and by sending teams to affected areas to conduct field reconnaissance and provide technical assistance to foreign partner agencies. The EHP also works with foreign partner agencies identified by the BHA to conduct joint science and monitoring projects, scientific exchanges, and trainings to build capacity. Mission alignment, planning, funding, and reporting related to this interagency response and capacity-building work are managed through an Earthquake Disaster Assistance Team (EDAT), developed by USGS and the legacy U.S. Office of Foreign Disaster Assistance, now BHA, in 2009 to respond to selected earthquake and landslide crises around the world and to build capacity within monitoring and research organizations in developing nations.

EDAT activities advance EHP’s science mission in ways that would be difficult to achieve through domestic work alone. EDAT scientists are exposed to a wider range of earthquake hazards and impacts than they can regularly observe in the United States, aiding preparedness for rare but potentially catastrophic domestic events. They gain new perspectives on research and response while working across a variety of tectonic, climate, and cultural settings. International work provides a unique opportunity to learn more effective strategies for the USGS to overcome barriers to providing earthquake science and risk information to domestic underserved communities. EDAT activities also help the EHP strengthen relationships with international counterparts and stakeholders working to advance earthquake science and engineering, such as the Global Earthquake Model (known as GEM) Foundation and GeoHazards International, that can be leveraged to help deliver domestic priorities. In this way, work conducted under the auspices of EDAT serves NHERP objectives while also contributing to knowledge and best practices for global earthquake risk reduction.

Over the coming decade, EDAT will work with BHA, EHP, USGS science center directors, EDAT scientists, and other relevant parties to prioritize resources in a way that benefits and aligns with the mission of both the BHA and EHP as a **foundational** priority. Historically, EDAT projects have been conducted in an ad hoc fashion, responding to individual requests for assistance. In the coming years, EDAT plans to strategically prioritize activities that fall within overlapping interest among these groups, and those with the highest potential to advance both the scientific and humanitarian objectives of the U.S. Government. EDAT leadership will issue targeted annual guidance that matches guidance provided by the BHA and EHP, identifying areas of overlap and opportunities that most closely align with mutually beneficial goals while keeping the needs and requests of international counterparts as a core philosophy.

EDAT plans to continue defining its unique role in the global earthquake risk-reduction environment and aims to direct resources towards high-impact activities. This includes strategically adding standing staff to address the most common international requests for assistance and to support the highest priorities of BHA and USGS as resources permit (fig. 20). EDAT will also leverage project activities to build the capacity of early- and mid-career scientists in project teams, incorporate diverse voices, fill existing gaps in talent or scientific knowledge, strengthen key relationships with international stakeholders, and provide opportunities for data access in regions that have limited seismic station coverage.

EDAT also plans to contribute to EHP priorities through the humanitarian and scientific opportunities afforded by associated work efforts. Prioritizing projects by strategic impact will enable participants, programs, centers, and the bureaus that support EDAT to leverage available resources and maximize the benefits to reduce human and economic losses related to global earthquakes.

Earthquake Disaster Assistance Team Engagement After 2023 Türkiye Earthquakes

In response to the 2023 Türkiye-Syria earthquakes, the Earthquake Disaster Assistance Team (EDAT) supported U.S. Government response to the earthquake sequence, providing critical situational awareness in the days, weeks, and months following the magnitude 7.8 mainshock, magnitude 7.5 aftershock, and subsequence earthquake sequence. Following the main humanitarian response, EDAT received substantial support from the U.S. Agency for International Development Bureau for Humanitarian Assistance to perform tasks aimed at reducing the human and economic consequences of future earthquakes in Türkiye and in similar seismically active regions worldwide. EDAT reconnaissance tasks were complementary to one another, yet shared the purpose to support resilience and reduce suffering following future earthquakes and were largely completed in response to requests by, and in collaboration with, Turkish colleagues.

Engagement began with an initial reconnaissance visit by a U.S. Geological Survey research civil engineer with ties to Turkish government and university response agencies. Bureau for Humanitarian Assistance funding subsequently supported six specific tasks. Task A aimed to characterize the extent of the faulted areas to inform land usage and zoning policies; task B aimed to document earthquake-triggered landslides that could be reactivated by rain or future earthquakes; task C involved a performance assessment of structures built in the past two decades that followed revised building-code provisions and improved construction methods; tasks D and E involved capacity building and training on best practices and software for structural health monitoring (instrumenting of buildings) and operational earthquake forecasting, activities not previously ongoing in Türkiye; and task F was designed to inform land usage, hazard assessment, and building-code improvements by extending seismometer coverage for aftershock detection over and beyond the rupture zones across the region. All these tasks were supplemented by other U.S. Geological Survey-focused efforts, including work on ground-motion models. This work also contributes to lessons captured under National Earthquake Hazards Reduction Program post-earthquake investigations (see “Earthquake-Response Coordination” section).

Geoscientists from the Earthquake Disaster Assistance Team visited a village in Türkiye that had been destroyed by an earthquake-triggered landslide in 2023 (task B). Photograph by Paula Burgi, U.S. Geological Survey.

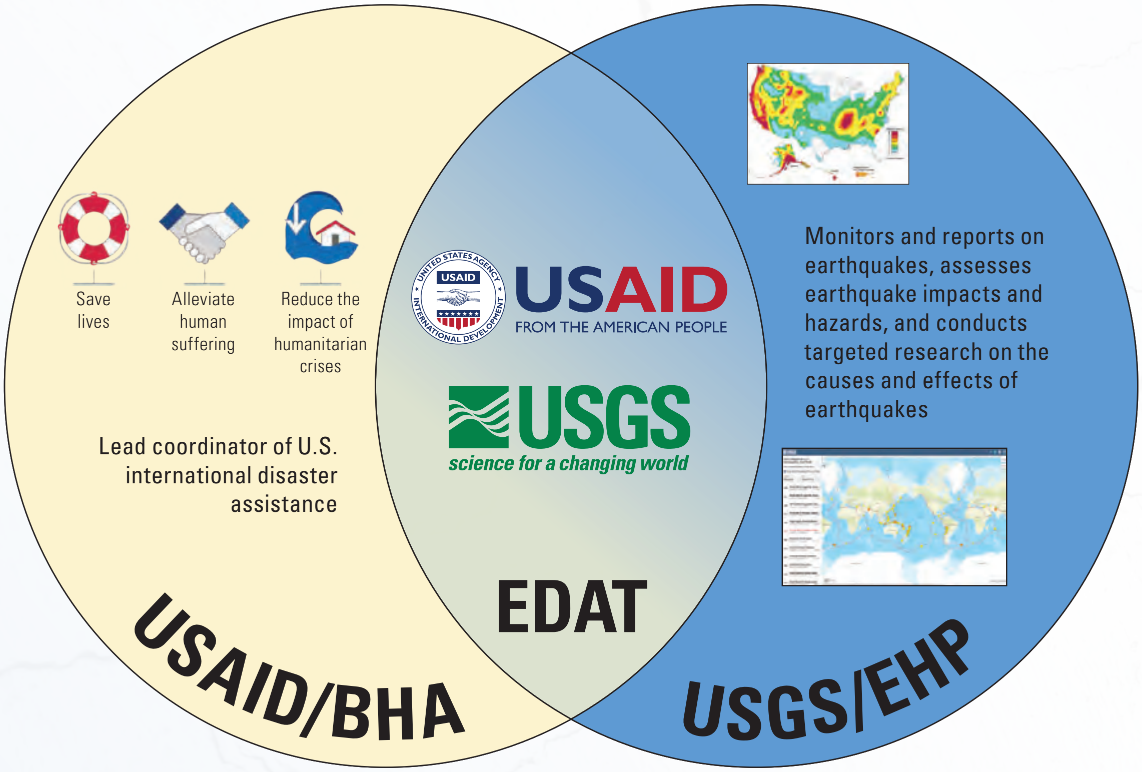


Figure 20. The mission of the Earthquake Disaster Assistance Team (EDAT) exists at the interface between the missions of the U.S. Agency for International Development (USAID) Bureau for Humanitarian Assistance (BHA), which is the lead coordinator of international disaster assistance by the U.S. Government, and the Earthquake Hazards Program (EHP). The activities and projects conducted by EDAT are mutually beneficial to USAID and the U.S. Geological Survey (USGS), as well as to foreign counterparts (images courtesy of Bureau for Humanitarian Assistance and U.S. Geological Survey).

A Vision for External Partnerships

The EHP provides significant support for external partners, averaging a little more than $28 million annually over FYs 2021–23. Much of this—approximately $22 million—supports cooperative agreements with monitoring partners within ANSS and ShakeAlert. The balance supports annual external grants and a cooperative agreement with the SCEC, which the USGS has supported since the SCEC's inception more than 30 years ago.

In general, the EHP seeks to support science that furthers our understanding of the genesis, propagation, characterization, and effects of earthquakes and that advances our ability to assess earthquake hazards and risks; to issue timely earthquake forecasts and warnings; to distribute rapid notifications of earthquake occurrence including their locations, source characteristics, and impacts; and to effectively communicate this information to support earthquake risk reduction. The scope and goals of external grants and agreements directly support science that cannot always be prioritized within the USGS because of a lack of personnel or expertise. However, flat funding for external grants since the 1990s has reduced the scope and quantity of these proposals and agreements, diminishing EHP's ability to meet external research goals across the program. This external research is often leveraged by funding from other groups, such as the Department of Energy, NSF, State agencies, and the USGS National Cooperative Geologic Mapping Program. Nonetheless, current limitations have, for example, diminished our ability to develop earthquake rupture simulators for use in the NSHM, develop State-specific Quaternary fault databases, and expand and test community models developed for Southern California. Given competing needs and different funding mechanisms, a strategic review of the external grants program, with input from external and internal voices, is needed, and thus, it is a **foundational** priority. Once such a review is complete, further investment in EHP's external assistance portfolio is an **aspirational** priority for the program.

Focused research centers external to the USGS may also pursue research goals of interest to the EHP (and other USGS programs), and so collaboration on aligned priorities may be of mutual benefit. When presented with opportunities to partner with external research centers to promote aligned efforts, similar to current funding provided to SCEC, the EHP will evaluate proposals according to the following themes.

1. Contributions towards understanding and assessing earthquake hazards and risks.
2. Level of hazard and risk in the geographic region of interest.
3. Degree to which improved scientific understanding may facilitate risk reduction.
4. Level of uncertainty in hazard estimates for the region of interest.
5. Degree to which community models can be fostered, maintained, and used to support improvements and advances in EHP flagship products.
6. Degree to which an external research center will drive institutional and multidisciplinary collaboration.
7. Degree to which an external research center will facilitate dissemination of scientific information to regional stakeholders.
8. Contributions towards established budget priorities for the EHP.

The EHP will naturally align most closely with those groups working on common priorities as outlined in this science strategy, in the USGS natural hazards science strategy (USGS Circular 1383–F, Holmes and others [2013]), and in the annual EHP External Grants Program proposal solicitation (released annually each spring; priorities for FY 2025 listed at the External Grants Program website, https://www.usgs.gov/programs/earthquake-hazards/science/external-grants-overview). It is also most advantageous if external groups seek to leverage partnerships with the USGS and other Federal and non-Federal agencies, emphasizing mutually beneficial scientific goals.

There are three main ways external research centers can interact with the USGS:

1. Scientific interactions. USGS scientists engage directly with research center committees, working groups, and organizational structure. This constitutes “in-kind” support and is a popular way for USGS scientists to become involved with external research activities that are closely aligned with the USGS mission.
2. External research grants. Non-USGS research groups can submit proposals to EHP’s external grants program in support of specific research projects.
3. Cooperative agreements. Research groups focused on topics closely aligned with EHP priorities and growth areas within the EHP budget may be appropriate for more significant budget support. Appropriations increases are likely necessary.

As the last point mentioned indicates, without a commensurate increase in budget, the EHP is unlikely to invest significantly in external research centers that represent new directions for the program—for example, in support of advancements in SZS. Expansion of SZS investment within the EHP and NHMA has been a priority within FY 2022–25 budget requests, and such an appropriations increase would be required for significant SZS-aligned ERC investment. Following the framework of program goals, support of SZS ERCs, or other such centers that expand program scope, can be considered an **aspirational** priority. For other ERCs that align with current programmatic scope and effort, EHP leadership will evaluate the proposal against the criteria outlined previously and in light of other programs, mission areas, and USGS priorities.

Subduction Zone Hazard and Risk Reduction

Subduction zones, where one tectonic plate collides with and is thrust over another, generate the world’s largest earthquakes, explosive volcanic eruptions, massive landslides, and powerful tsunamis. Subduction zones generate hazards straddling onshore and offshore environments in the Pacific Northwest (within the Cascadia Subduction Zone), southern Alaska (Alaska-Aleutian Subduction Zone), and the Caribbean and Pacific island territories. Tsunami hazards extend to Hawai‘i, California, and Atlantic coast States. Subduction zones are prone to cascading earthquake hazards (such as tsunamis, landslides, liquefaction, and fire), and quantifying their combined hazard potential requires comprehensive investigations. Yet subduction zones remain poorly understood because most of the processes that drive the hazard and risk lie offshore. Future disastrous events in these regions are inevitable, and investment in SZS to inform a broad range of decisions at all levels of society can help to make our Nation more resilient to these threats.

Despite extraordinary logistical challenges and high noise levels associated with studying offshore environments, recent technological advances are making it increasingly possible to characterize earthquake processes in these places. Through partnering among multiple institutions, data from seismic and geodetic monitoring, subsurface imaging, bathymetric mapping, and material sampling beneath the oceans and lakes now demonstrate that the same or better measurement resolution may be achieved offshore as onshore. A few particularly exciting endeavors underway include nimble, low-cost wave-glider seafloor geodetic deployments, which are autonomous floating vessels that can be used to gather ocean-based data, including from seafloor geodetic monuments; repurposing of the vast network of submarine fiber optic communications cables to measure strains and displacements in previously completely unsampled regions; and multisensor downhole arrays that have detected likely fluid, pore pressure, and fault slip transients.

Hebgen Lake fault scarp in 1959 after the August 18, 1959, magnitude 7.2 Hebgen Lake, Montana, earthquake. Photograph by J.R. Stacy, U.S. Geological Survey.

SZS has been a focus of effort across NHMA programs for several years; however, the funding necessary to significantly advance our understanding of these hazardous regions is lacking. The USGS has requested funding increases in FYs 2022–24, and again in FY 2025 to accelerate the implementation of the USGS SZS plan, "Reducing Risk Where Tectonic Plates Collide" (USGS Circular 1428, Gomberg and others [2017]). That plan describes work necessary to support investment in multihazards SZS across USGS mission areas and programs. The focus is on improving our understanding of risks posed to vulnerable communities in domestic subduction zone environments and delivering scientific information and tools to support risk reduction. Implementing the SZS plan remains the primary focus of SZS efforts both within the EHP and across the NHMA.

During summer 2021, the NHMA established an SZS working group internally at the USGS, populated by scientists from across our programs and centers, and serving as a resource for the NHMA and as a conduit of information to USGS leadership. This group is catalyzing effort to understand the full breadth of SZS work across USGS and is using this information to update USGS SZS priorities. In support of its work, the group organized an SZS workshop in January 2023 that involved USGS scientists and members of the external scientific community, including academic groups focused on subduction zones such as SZ4D (https://www.sz4d.org/), CRESCENT (https://cascadiaquakes.org/), and State partners. Although recent, the outcomes of the workshop will help USGS to internally prioritize SZS-focused research and monitoring in the future should additional funding become available.

In lieu of permanent funding increases to support expanded activities in SZS, one-time funding has been used to support high-priority activities. At the end of FY 2021, the Coastal and Marine Hazards and Resources Program within the NHMA, and the EHP, supported the acquisition of a new wave glider for sea floor geodesy work. The USGS wave gliders facilitate the nimble collection of seafloor geodetic data without the need for expensive ship time and were used both in 2020 and 2021 to collect such data after major subduction zone earthquakes along the Alaska-Aleutian Arc. At the end of FY 2022, EHP provided funding for two additional GNSS-acoustic[3] sites (each made up of a triangle of transponders) to an NSF community proposal for Cascadia and Alaska subduction zone studies (Award Abstract no. 2232638; "Collaborative Research—Near-Trench Community Geodetic Experiment"). The commitment of these sites, on the overriding plate associated with Gorda Plate subduction offshore Northern California, effectively leveraged the NSF investment by allowing 1 of the 12 total planned NSF sites to be moved to Alaska. The EHP repeated this investment at the end of FY 2023, providing funding for one additional GNSS-acoustic Gorda Plate site. The combined result is nine new Cascadia sites and six new Alaska sites, which help to improve the characterization of subduction zone interface locking, and thus hazard extent, in both Cascadia and Alaska. The EHP and other NHMA programs plan to continue to prioritize SZS support in the future as opportunities arise.

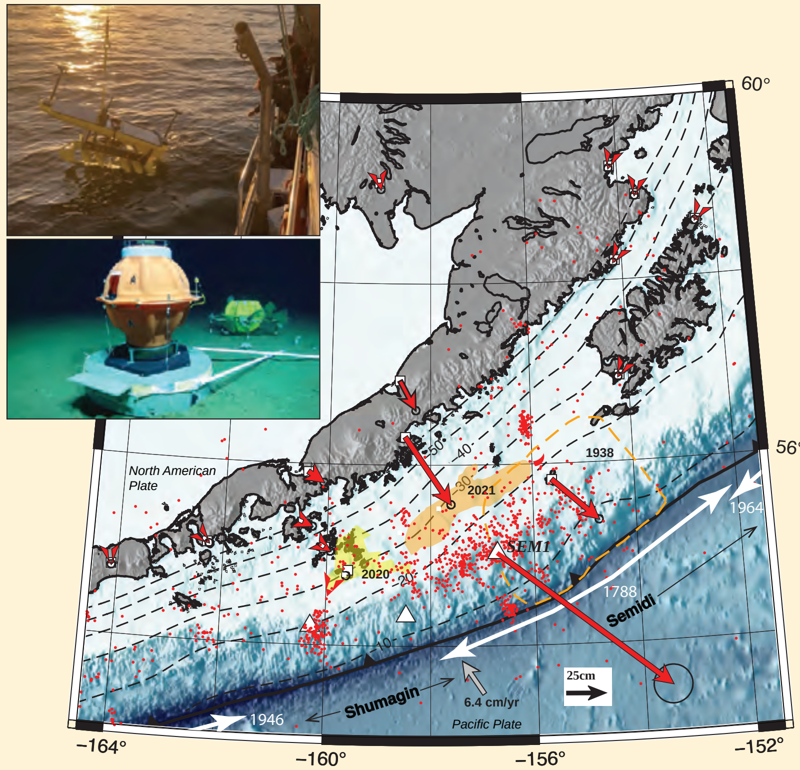
Language in the joint explanatory statement by Congress for the Department of the Interior, Environment, and Related Agencies Appropriations Bill and in the House markup has for several years expressed concern about a lack of investment in offshore instrumentation in the Cascadia Subduction Zone, as part of ShakeAlert and broader program direction: "Concerns remain regarding the lack of knowledge and offshore real-time instrumentation available for the Cascadia subduction zone. Our increased scientific understanding of earthquakes and the ocean environment will benefit from the wealth of offshore data collected" (U.S. House of Representatives, 2023). Further investment in SZS research and scientific infrastructure would help resolve these concerns and is a broad goal of NHMA programs and recent appropriations requests in FYs 2022–24. Further growth of SZS investment remains an **aspirational** priority for EHP and other NHMA programs and would support many of the key issues identified in other foundational and aspirational priorities throughout this plan. Although funding levels required for expansion of our SZS portfolio are significant—particularly those aspects that would involve offshore monitoring and research activities—the commensurate potential benefits are also significant, including for program priorities such as earthquake early warning, where telemetered offshore instrumentation could significantly improve both the timing and accuracy of life-safety warnings. For such endeavors, the EHP should undertake a benefit-cost analysis to understand if the potential improvements through such investment would outweigh the price tag involved.

---

[3]The global navigation satellite system-acoustic ranging combination technique is a seafloor geodetic technique that enables precise global seafloor positioning. The technique requires a sea surface observation platform that combines global navigation satellite system positioning and acoustic ranging.

Seafloor Geodesy

Subduction zone earthquakes and tsunami are some of Earth's most impactful and societally relevant hazards, yet because of their challenging environments, subduction zone megathrust faults are exceptionally sparsely instrumented. New seafloor geodetic techniques, in particular the global navigation satellite system-acoustic method, permit centimeter-scale displacement measurements from these zones. The measurements are facilitated by using an autonomous surface vessel, called a "wave glider." In recognition of the significant impact that these observations will make on imperative natural hazards and science objectives, the Earthquake Hazards Program and the Coastal and Marine Hazards and Resources Program within the Natural Hazards Mission Area of the U.S. Geological Survey (USGS) have formed a seafloor geodesy collaboration. The USGS wave glider was used both in 2020 and 2021 to collect data after major subduction zone earthquakes along the Alaska-Aleutian Arc (see figure on the 2021 Chignik earthquake). In addition to fostering very positive and productive interagency cooperative efforts (between the Earthquake Hazards Program and Coastal and Marine Hazards and Resources Program), the seafloor geodesy program positions USGS at the cutting edge of the general subduction zone science academic community in terms of community leadership (through invited talks and workshop organization) and leveraged participation in proposals from diverse funding bodies such as the National Science Foundation and the National Oceanic and Atmospheric Administration.



Example of the use of seafloor geodesy to better characterize offshore earthquake-related displacement. This figure shows the magnitude 8.2 earthquake displacement field in Chignik, Alaska, 2021. Red arrows are vectors representing cumulative co- and post-seismic displacement. Station SEM1 is a seafloor geodesy, global navigational satellite system-acoustic site, data from which were recovered using the U.S. Geological Survey wave glider; other vectors are land-based global navigational satellite system stations. Red circles are aftershocks. Polygons and white arrows are extent of previous earthquake ruptures. Inset photographs show the wave glider (top) and seafloor transponder (bottom), both of which were integral to this study (images modified from Brooks and others [2023a], licensed under the Creative Commons Attribution 4.0 International license).

Social Science

Since the inception of the ShakeAlert project, social science has become integral to advancing its goals through research and understanding of the human interface of EEW—how users interact with this critical life-safety system. Consideration of social science in ShakeAlert design and planning results in positive impacts to public safety. Social science has contributed to determinations of alert delivery thresholds, alert message content, and postalert communication and stakeholder engagement and interactions. Social science has also played a central role in the ShakeAlert Joint Committee on Communication, Education, Outreach, and Technical Engagement through support of educational products and programs.

In the future, social science can contribute to a broad array of activities across the EHP by facilitating advances in risk communication, education and outreach, and the understanding of human attitudes and behavior in earthquake product design, development, and distribution. All these advances optimize the EHP's overall effectiveness. Social science research has played an integral role in the development of messaging for the EHP OAF product (Michael and others, 2020), and in particular the scenario-based approach to those forecasts (for example, McBride and others, 2019). Social science is also contributing to an improved understanding of how to incorporate equitable risk strategies into earthquake information product design (Jenkins and others, 2022; Loos and others, 2024). Further, the USGS's "Did You Feel It?"

product has added a series of questions on demographics and EEW systems to better understand how people use these systems globally (Goltz and others, 2022).

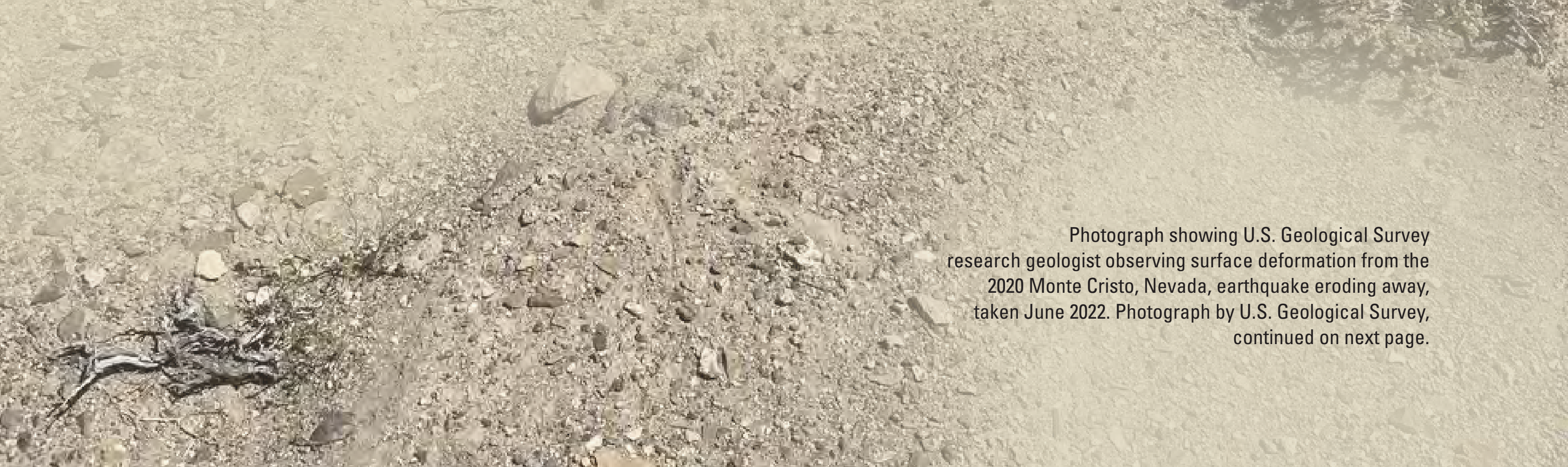
Despite the clear opportunities to support EHP science, the program has had limited capacity to grow the footprint of social science research, and staff is currently limited to just one permanent employee. Although this capacity can be supplemented by external social scientists, having an internal resource to frame critical priorities, and to maintain the quality of social science produced on behalf of the USGS, would be beneficial for the agency. Without internal resources, external research can be funded but will lack coordination mechanisms, quality control, and the ability to assess the veracity and applicability of the research generated. Further, having internal capacity provides agility and the ability to apply social science to critical EHP products. Application requires significant investment in learning operational procedures and processes within the USGS. Given the clear benefits of having internal social scientists, an **aspirational** priority of this plan is to expand the cohort of social science researchers within the EHP, furthering our ability to advance program priorities and goals as they interface with stakeholders.

U.S. Geological Survey Coordination

The USGS recently published a long-term vision for integrated science across the bureau, called “U.S. Geological Survey 21st Science Strategy, 2020–2030” (USGS, 2021). The document presents a five-pronged strategic approach to science efforts, involving (1) a scientific focus driving improved interdisciplinary science, (2) a technological focus on IT infrastructure, (3) a focus on partnership to strengthen external engagement, (4) an organizational focus to optimize interactions across the USGS, and (5) an overarching focus on developing integrative and predictive science capacity bureau-wide.

Many of these USGS-wide goals are well aligned with ongoing EHP efforts and with priorities outlined in this document. Our flagship products through the ANSS, ShakeAlert, and NSHM are all built upon pivotal partnerships with the external community, through RSNs, Federal and State partners, external research grants, engagement with external research centers like the SCEC, and interpersonal agreements with specific academic researchers. Private partnerships like those with The Gordon and Betty Moore Foundation have also helped drive growth of ShakeAlert and ANSS. EHP goals under NEHRP are driven through partnership with NIST, FEMA, NSF, and others, as reflected in the NEHRP strategic plan (NEHRP, 2023). The GSN is itself a partnership with NSF, and the long-term growth, stability, and innovation of this critical network relies on its use throughout the external research community. Partnership with BHA has contributed significantly to the PAGER and OAF products, as well as to other international engagement efforts of the program. Other key products, such as ShakeCast, have also benefitted from significant external partnerships. The NSMP relies on engagement and interactions with the California Geological Survey and the U.S. Department of Veterans Affairs. As discussed in the “A Vision for External Partnerships” section, expanding partnerships with external research centers, including in SZS, remains a central goal of the EHP if commensurate funding increases are made available. Thus, partnership is central to the EHP mission.

The EHP and GSN also contribute to USGS responsibilities under the Tsunami Warning, Education, and Research Act of 2017 (33 U.S.C. 3201 et seq.). This involves seismic and geodetic data sharing between EHP/GSN and NOAA Tsunami Warning Centers (TWCs), earthquake monitoring and information sharing between EHP and NOAA TWCs, and work with the National Tsunami Hazard Mitigation Program. NOAA TWCs are particularly dependent on GSN data because of the network’s global coverage, high quality, and very-broadband instrumentation that is specially designed to accurately characterize the great-sized subduction zone earthquakes that are most likely to produce devastating tsunamis. The EHP plans to continue these activities as a **foundational** priority.



Photograph showing U.S. Geological Survey research geologist observing surface deformation from the 2020 Monte Cristo, Nevada, earthquake eroding away, taken June 2022. Photograph by U.S. Geological Survey, continued on next page.

Similarly, IT infrastructure is pivotal to the EHP mission, and significant investment has been made to modernize computational architecture across the program to meet the demands of rapid and reliable information distribution and services while maintaining a secure and robust IT framework as the foundation for 24/7 operations. EHP websites receive tens of millions of hits per day outside of significant earthquake activity and millions of hits per minute in the aftermath of significant earthquakes. A modern and robust IT infrastructure is critical to support this dynamic usage. The EHP is supporting ongoing efforts to migrate more systems and infrastructure to the cloud, thereby providing more robustness and flexibility, improving efficiency, and hopefully reducing long-term operational cost. The USGS has requested funding increases in FYs 2022, 2023, and 2024 to modernize and harden IT infrastructure in support of earthquake analysis and to ensure the robust delivery of enhanced multihazards products like PAGER. The final FY 2023 budget partially supported this request. Continued investment in these activities is a **foundational** priority of this plan.

Other USGS goals speak to the need for expanded cross-program and pan-mission-area science activities through integrated, cross-disciplinary science efforts. The EHP has recently been involved in integrated science activities focused on geologic carbon sequestration. Geologic carbon sequestration offers the potential to reduce carbon emissions in the atmosphere and offset new carbon dioxide emissions by providing long-term, safe, and effective sequestration of greenhouse gases in geologic formations. However, there are associated risks related to anthropogenic earthquakes (induced seismicity) caused by sequestration. Such seismicity has been predominantly small in magnitude, with no impact to date, but scientific understanding between sequestration and induced seismicity is not as advanced as for oil and gas activities. Thus, further research into the influence of having two fluids of different densities in the triggering process for associated earthquakes is needed to adapt previously developed methods to carbon sequestration. USGS budget requests in FYs 2022 and 2023 have supported expanded induced seismicity activities, though funding is yet to be appropriated. Further growth of induced seismicity investment in support of cross-disciplinary science goals at the USGS remains an **aspirational** priority. The EHP also plans to continue to engage with integrated science discussions across the USGS and, as opportunities arise, will seek to support collaborative activities.

In addition to USGS science focus strategies, the EHP also supports the priorities of the Secretary of the Interior, including advancing efforts to support underserved communities, and focusing on environmental justice by engaging with marginalized groups in science planning efforts. These topics are expanded upon further in the “Diversity, Equity, Inclusion, and Accessibility” section.

U.S. Geological Survey/Geologic Hazards Science Center site characterization team member working with the assistance of U.S. Navy sailors to perform a three-dimensional seismic survey over the Utsalady Point fault, Naval Air Station Whidbey Island, Washington, August 7, 2023.
Photograph by Alena Leeds, U.S. Geological Survey.

Diversity, Equity, Inclusion, and Accessibility

USGS science, and in turn, EHP science, is intended to serve the needs of all Americans, and the USGS has committed to incorporating DEIA into all components of bureau activities. As a program within the NHMA, the EHP is working to understand the needs of historically underserved communities in its efforts to research hazard, reduce risk, and communicate critical information on hazard and risk mitigation. DEIA are central tenants of EHP science planning efforts.

Within the NHMA, the Risk COP is spearheading DEIA efforts across hazard programs. Through the Risk COP, hazards scientists are collaborating with communities to develop actionable science and tools to facilitate risk reduction. Efforts follow the priorities laid out in the USGS plan for risk research (Ludwig and others, 2018) and focus on delivering actionable risk information to decision makers and to the public, while actively engaging these communities in research and product development. The Risk COP recently published a strategic approach to incorporating equity more deliberately into future risk research activities (Brooks and others, 2023b), which can act as a guide for the EHP and the USGS more broadly.

Two recent research efforts within ShakeAlert have focused on DEIA. First, Jenkins and others (2022) review aspects of social vulnerability as they relate to ShakeAlert, contributing to important conversations about DEIA issues within EEW and earthquake preparedness campaigns in general. In McBride and others (2022), the authors compile evidence from around the world to inform policies on the most effective protective actions following EEW alerts. As discussed in the “Social Science” section, current efforts are also attempting to incorporate equitable risk strategies into earthquake information product design. In 2023, the EHP led a series of 15 virtual focus groups of disaster management professionals whose work prioritizes socially vulnerable populations. The findings from these engagements are guiding improvements to the PAGER product. The same team has conducted user demographic research on equity issues related to the “Did You Feel It?” system. One outcome of this work has identified the need for multilanguage options, leading to the Did You Feel It? questionnaire being translated into several key languages (adding Chinese, Arabic, French, German, and others to English and Spanish drop-down menus), which went live on EHP event pages in October 2023.

The FY 2023 EHP external grants program announcement (released in March 2022) included new language encouraging proposals focused on research targeting earthquake hazard mitigation and risk reduction in underserved communities and in populations whose vulnerability may be directly related to socioeconomic factors. Additional language is planned for the upcoming FY 2025 announcement and cycle.

DEIA has also been a focus within EHP-funded science centers, at both ESC and GHSC, where scientist-led efforts are focusing on DEIA across science projects, in hiring practices, and in community engagement and outreach efforts. Both centers have expanded their internship programs to reach a more diverse audience of candidates. Alongside the USGS Mendenhall Program, summer internships from the undergraduate level offer excellent opportunities for recruitment into the EHP, where a diverse workforce can help strengthen the program’s commitment and success in reaching diverse communities. This theme has also been a recent recommendation from the SESAC (Beroza and others, 2022), in addition to a continued focus on hazards assessment and risk mitigation measures to help understand inequities in how risk affects disadvantaged communities. A **foundational** priority of this plan is the continued and expanded incorporation of DEIA activities in EHP science, information distribution, community engagement, and external funding activities.

Unburied underground vault at Global Seismographic Network station QSPA, South Pole, Antarctica, January 30, 2020. Photograph by Edward Kromer, KBR, Inc., under contract to the U.S. Geological Survey, continued on next two pages.

Conclusions

This plan outlines prioritized strategic goals for research and operations across the U.S. Geological Survey Earthquake Hazards Program (EHP), which will be used to guide program activities over the next decade. Over the major subcomponents of the program, this plan has laid out both **foundational** and **aspirational** priorities, emphasizing those activities which must be maintained under level or declining budgets, and those where the EHP would most beneficially expand if funding opportunities arise.

Several themes stand out as being most critical to the EHP over the next decade.Across all coordination areas

1. System-level science. There is a critical need for integration across the EHP's coordination areas, products, and underlying projects to improve consistency and maximize efficiency. These developments will benefit many EHP products. This will be a focus of EHPC discussion over the next 2 years, with a goal of identifying duplicative effort and providing recommendations for gaining efficiency.

In earthquake monitoring

2. Working toward an automated earthquake processing pipeline. The incorporation of machine learning and artificial intelligence techniques to earthquake monitoring procedures represents perhaps one of the most influential opportunities for revolutionizing our approaches to operational network seismology. Such advancements could improve underlying catalogs and seismological data while reducing costs. Key to implementation within the EHP and Advanced National Seismic System will be the coordination across regions and networks.
3. Enhance the accuracy and reliability of the ShakeAlert Earthquake Early Warning system and plan for extension to other regions. Encompassing many of the ShakeAlert priorities, this goal summarizes the need to improve current operational procedures and system accuracy and then look to extend capabilities to other at-risk regions of the United States.

In assessments of hazard and risk

4. Time-dependent earthquake forecasting. There is a growing need to provide critical hazard information to a broader portfolio of users beyond the building-code community, and many of those stakeholders require hazard information on shorter time scales than typical

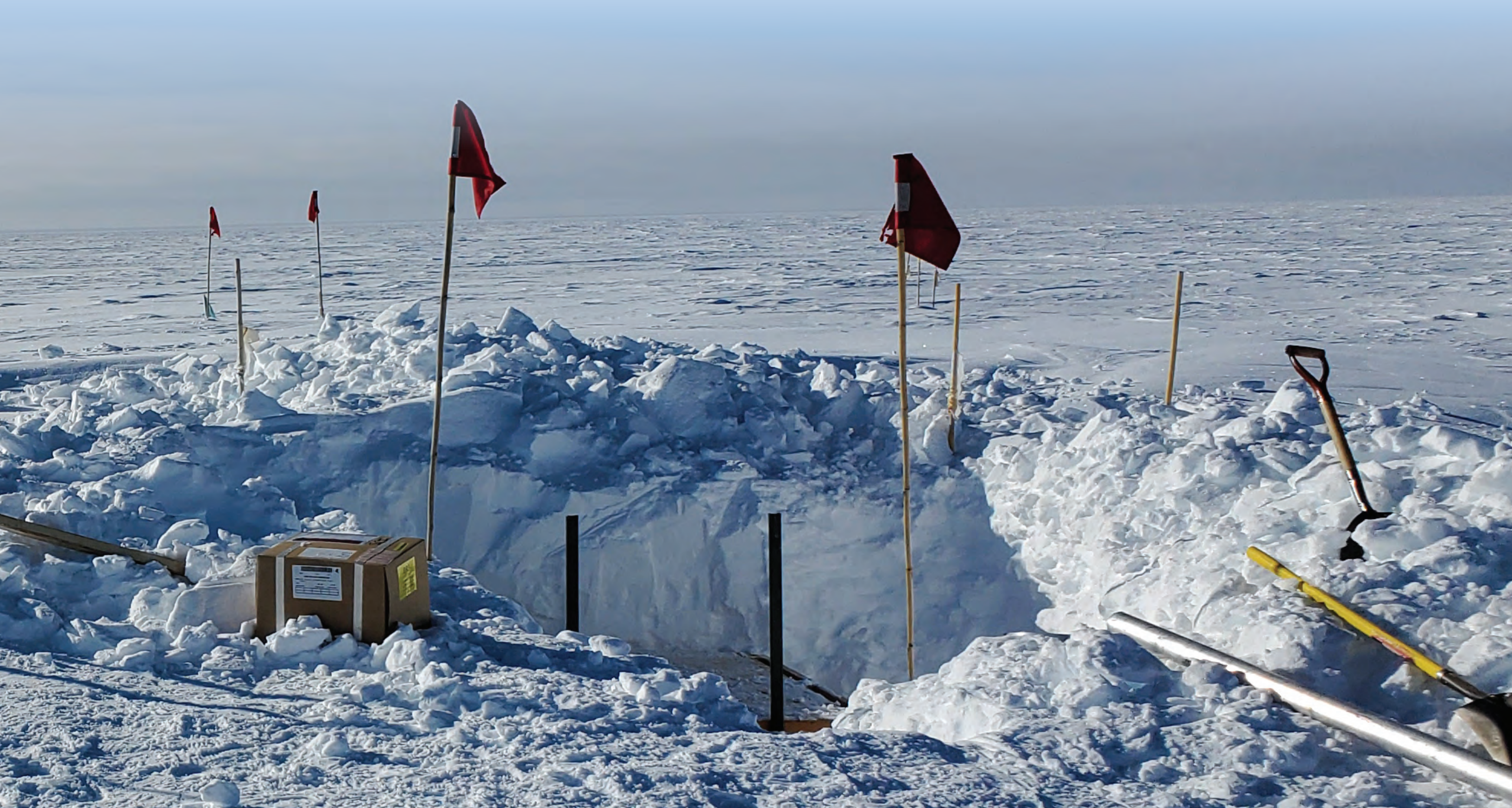
time independent analyses facilitate and for seismic hazards that vary through time. Hence, there is a growing call for time-dependent models and for a broadening suite of hazard and risk forecast and assessment products. The U.S. Geological Survey EHP is best positioned to provide such actionable information.

In targeted research

5. Physically realistic model development. This goal encompasses a number of priorities across EHP research coordination areas, including support for multicycle physics-based earthquake simulators, advancing physics-based models of earthquake rupture; improving earthquake forecasts through the use of physically realistic models, and use of physics-based ground-motion simulations. Coordination across these varied requirements will offer the best opportunity for making advances that benefit multiple efforts. Progress on these topics will significantly advance our understanding of earthquake processes and will in turn improve hazard characterization, as discussed previously.

6. Expanded computational capacity. EHP products and modeling frameworks increasingly require significant computational resources to operate and maintain. Processing associated datasets, which are growing in size and complexity, also require access to high-performance computing capacity. System-level science capabilities and the integration of modeling approaches across projects will also likely require advanced computational resources. Some systems—for example, within aspects monitoring operations, and product support—also leverage cloud resources, and associated needs will continue to grow. These priorities call for coordinated approaches to address computational needs.

Each of these priorities is rooted in the EHP's mission to monitor and provide timely information of earthquakes and their impact, to provide actionable assessments of earthquake hazards, to advance the understanding of earthquakes, and to make advances in earthquake risk reduction. The EHP strives to deliver this information to all communities at risk, making diversity, equity, inclusion, and accessibility a core tenet in the execution of this science strategy. Implementing these goals and other items described in this plan will help the EHP maintain its position as a leading resource for earthquake information and research to meet the rapid and evolving needs of the diverse communities the program serves.



References Cited

Aagaard, B., Celebi, M., Gee, L., Graves, R., Jaiswal, J., Kalkan, E., Knudsen, K., Luco, N. Smith, J., Steidl, J., and Stephens, C., 2017, U.S. Geological Survey National Strong-Motion Project strategic plan, 2017–22: U.S. Geological Survey Open-File Report 2017–1156, 14 p., accessed September 6, 2024, at https://doi.org/10.3133/ofr20171156.

Anthony, R.E., Ringler, A.T., and Wilson, D.C., 2018, Improvements in absolute seismometer sensitivity calibration using local Earth gravity measurements: Bulletin of the Seismological Society of America, v. 108, no. 1, p. 503–510. [Also available at https://doi.org/10.1785/0120170218.]

Beroza, G.C., Long, M.D., Velasco, A.A., Abercrombie, R.E., Hamburger, M.W., Bürgmann, R., Pekelnicky, R.G., Melbourne, T.I., Anderson, J.G., and Meltzer, A.S., 2022, SESAC letter to the USGS Director: Scientific Earthquake Studies Advisory Committee, 4 p., accessed October 2022 at https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/media/files/sesac_22report.pdf.

Böse, M., Andrews, J., Hartog, R., and Felizardo, C., 2023, Performance and next-generation development of the Finite-Fault Rupture Detector (FinDer) within the United States West Coast ShakeAlert warning system: Bulletin of the Seismological Society of America, v. 113, no. 2, p. 648–663. [Also available at https://doi.org/10.1785/0120220183.]

Brocher, T.M., Gefeke, K., Boatwright, J., and Knudsen, K.L., 2018, Reported investments in earthquake mitigation top $73 to $80 billion in the San Francisco Bay Area, California, since the 1989 Loma Prieta earthquake: U.S. Geological Survey Open-File Report 2018–1168, 18 p., accessed September 6, 2024, at https://doi.org/10.3133/ofr20181168.

Brooks, B.A., Goldberg, D., Desanto, J., Ericksen, T.L., Webb, S.C., Nooner, S.L., Chadwell, C.D., Foster, J., Minson, S., Witter, R., Haeussler, P., Freymueller, J., Barnhart, W., and Nevitt, J., 2023a, Rapid shallow megathrust afterslip from the 2021 M8.2 Chignik, Alaska earthquake revealed by seafloor geodesy: Science Advances, v. 9, no. 17, article eadf9299, 10 p., accessed September 6, 2024, at https://doi.org/10.1126/sciadv.adf9299.

Brooks, E., Pennaz, A., and Jurjonas, M., 2023b, U.S. Geological Survey risk research community of practice 2021 workshop report—Workshop on considering equitable engagement in research design: U.S. Geological Survey Open-File Report 2023–1072, 25 p., accessed September 6, 2024, at https://doi.org/10.3133/ofr20231072.

Chung, A.I., Henson, I., and Allen, R.M., 2019, Optimizing earthquake early warning performance—ElarmS-3: Seismological Research Letters, v. 90, no. 2A, p. 727–743. [Also available at https://doi.org/10.1785/0220180192.]

Cochran, E.S., Rubinstein, J.L., Barbour, A.J., and Kaven, J.O., 2024, Induced seismicity strategic vision: U.S. Geological Survey Circular 1509, 39 p., accessed September 6, 2024, at https://doi.org/10.3133/cir1509.

Cochran, E.S., Saunders, J.K., Minson, S.E., Bunn, J., Baltay, A., Kilb, D., O'Rourke, C., Hoshiba, M., and Kodera, Y., 2022, Alert optimization of the PLUM earthquake early warning algorithm for the western United States: Bulletin of the Seismological Society of America, v. 112, no. 2, p. 803–819. [Also available at https://doi.org/10.1785/0120210259.]

Federal Emergency Management Agency and National Institute of Standards, 2021, Recommended options for improving the built environment for post-earthquake reoccupancy and functional recovery time: Federal Emergency Management Agency FEMA P-2090/NIST SP-1254, 115 p., accessed September 6, 2024, at https://doi.org/10.6028/NIST.SP.1254.

Field, E.H., 2022, Some systemic risks to progress on seismic hazard assessment: Seismological Research Letters, v. 93, no. 2A, p. 513–516. [Also available at https://doi.org/10.1785/0220210268.]

Field, E.H., Jordan, T.H., Page, M.T., Milner, K.R., Shaw, B.E., Dawson, T.E., Biasi, G., Parsons, T.E., Hardebeck, J.L., Michael, A.J., Weldon, R.J., Powers, P.M., Johnson, K.M., Zeng, Y., Bird, P., Felzer, K., van der Elst, N., Madden, C., Arrowsmith, R., Werner, M.J., and Thatcher, W.R., 2017, A synoptic view of the Third Uniform California Earthquake Rupture Forecast (UCERF3): Seismological Research Letters, v. 88 no. 5, p. 1259–1267. [Also available at https://doi.org/10.1785/0220170045.]

Given, D.D., Allen, R.M., Baltay, A.S., Bodin, P., Cochran, E.S., Creager, K., de Groot, R.M., Gee, L.S., Hauksson, E., Heaton, T.H., Hellweg, M., Murray, J.R., Thomas, V.I., Toomey, D., and Yelin, T.S., 2018, Revised technical implementation plan for the ShakeAlert system—An earthquake early warning system for the West Coast of the United States: U.S. Geological Survey Open-File Report 2018–1155, 42 p., accessed September 6, 2024, at https://doi.org/10.3133/ofr20181155. [Supersedes USGS Open-File Report 2014–1097.]

Goltz, J.D., Wald, D.J., McBride, S.K., DeGroot, R., Breeden, J., and Bostrom, A., 2022, Development of a companion questionnaire for "Did You Feel It?"—Assessing response in earthquakes where an earthquake early warning may have been received: Earthquake Spectra, v. 39, no. 1, p. 434–453. [Also available at https://doi.org/10.1177/87552930221116133.]

Gomberg, J.S., Ludwig, K.A., Bekins, B., Brocher, T.M., Brock, J., Brothers, D.S., Chaytor, J.D., Frankel, A., Geist, E.L., Haney, M.M., Hickman, S.H., Leith, W.S., Roeloffs, E.A., Schulz, W.H., Sisson, T.W., Wallace, K.L., Watt, J., and Wein, A.M., 2017, Reducing risk where tectonic plates collide—U.S. Geological Survey subduction zone science plan: U.S. Geological Survey Circular 1428, 45 p., accessed September 6, 2024, at https://doi.org/10.3133/cir1428.

Hayes, G.P., Earle, P. S., Benz, H.M., Wald, D.J., and Yeck, W.L., 2019, National Earthquake Information Center strategic plan, 2019–23: U.S. Geological Survey Circular 1457, 17 p., accessed September 6, 2024, at https://doi.org/10.3133/cir1457.

Heppermann, B., and Luco, N., 2020, Exploring the use of "M9" ground motions simulations for seismic risk assessment of dams, *in* Proceedings of the 17th World Conference on Earthquake Engineering, Sendai, Japan, September 13–18, 2020: Kanpur, India, National Information Centre of Earthquake Engineering, 12 p.

Holmes, R.R., Jr., Jones, L.M., Eidenshink, J.C., Godt, J.W., Kirby, S.H., Love, J.J., Neal, C.A., Plant, N.G., Plunkett, M.L., Weaver, C.S., Wein, A., and Perry, S.C., 2013, U.S. Geological Survey natural hazards science strategy—Promoting the safety, security, and economic well-being of the Nation: U.S. Geological Survey Circular 1383–F, 79 p., accessed September 6, 2024, at https://doi.org/10.3133/cir1383F.

Holzer, T.L., Borcherdt, R.D., Comartin, C.D., Hanson, R.D., Scawthorn, C.R., Tierney, K., and Youd, T.L., 2003, The plan to coordinate NEHRP post-earthquake investigations: U.S. Geological Survey Circular 1242, 27 p., accessed September 6, 2024, at https://doi.org/10.3133/cir1242.

Jaiswal, K.S., Bausch, D., Rozelle, J., Holub, J., and McGowan, S., 2017, Hazus® estimated annualized earthquake losses for the United States: Federal Emergency Management Agency, FEMA P-366, 76 p.

Jaiswal, K.S., Rozelle, J., Tong, M., Sheehan, A., McNabb, S., Kelly, M., Zuzak, C., Bausch, D., Sims, J., 2023, Hazus estimated annualized earthquake losses for the United States: Federal Emergency Management Agency, FEMA P-366, 96 p. [Also available at https://www.fema.gov/sites/default/files/documents/fema_p-366-hazus-estimated-annualized-earthquake-losses-united-states.pdf.]

Jenkins, M.R., McBride, S.K., Morgoch, M., and Smith, H., 2022, Considerations for creating equitable and inclusive communication campaigns associated with ShakeAlert, the earthquake early warning system for the West Coast of the USA: Disaster Prevention and Management, v. 31, no. 1, p. 79–91. [Also available at https://doi.org/10.1108/DPM-03-2021-0090.]

Kwong, N.S., and Jaiswal, K.S., 2023, A methodology to combine shaking and ground failure models for forecasting seismic damage to buried pipeline networks: Bulletin of the Seismological Society of America, v. 113, no. 6, p. 2574–2595. [Also available at https://doi.org/10.1785/0120220132.]

Loos, S., Karr, M., Macías, M., Knodel, E., Wald, D., Ludwig, K., Peek, L., and Lee, P., 2024, Publicly available yet not fully accessible—Strategies for equitably sharing post-earthquake loss information: Proceedings of the 18th World Conference on Earthquake Engineering, Milan, July 2024, accessed September 10, 2024, at https://www.wcee2024.it/2024/06/28/conference-proceedings/.

Ludwig, K.A., Ramsey, D.W., Wood, N.J., Pennaz, A.B., Godt, J.W., Plant, N.G., Luco, N., Koenig, T.A., Hudnut, K.W., Davis, D.K., and Bright, P.R., 2018, Science for a risky world—A U.S. Geological Survey plan for risk research and applications: U.S. Geological Survey Circular 1444, 57 p., accessed September 6, 2024, at https://doi.org/10.3133/cir1444.

McBride, S.K., Llenos, A.L., Page, M.T., and van der Elst, N., 2019, #EarthquakeAdvisory—Exploring discourse between government officials, media, and social media during the 2016 Bombay Beach swarm: Seismological Research Letters, v. 91, no. 1, p. 438–451. [Also available at https://doi.org/10.1785/0220190082.]

McBride, S.K., Smith, H., Morgoch, M., Sumy, D., Jenkins, M., Peek, L., Bostrom, A., Baldwin, D., Reddy, E., de Groot, R., Becker, J., Johnston, D., and Wood, M., 2022, Evidence-based guidelines for protective actions and earthquake early warning systems: Geophysics, v. 87, no. 1, p. WA77–WA102. [Also available at https://doi.org/10.1190/geo2021-0222.1.]

Michael, A.J., McBride, S.K., Hardebeck, J.L., Barall, M., Martinez, E., Page, M.T., van der Elst, N., Field, E., Milner, K., and Wein, A.M., 2020, Statistical seismology and communication of the USGS operational aftershock forecasts for the 30 November 2018 Mw 7.1 Anchorage, Alaska, earthquake: Seismological Research Letters, v. 91 no. 1, p. 153–173. [Also available at https://doi.org/10.1785/0220190196.]

Murray, J.R., Crowell, B.W., Murray, M.H., Ulberg, C.W., McGuire, J.J., Aranha, M.A., and Hagerty, M.T., 2023, Incorporation of real-time earthquake magnitudes estimated via peak ground displacement scaling in the ShakeAlert earthquake early warning system: Bulletin of the Seismological Society of America, v. 113, no. 3, p. 1286–1310. [Also available at https://doi.org/10.1785/0120220181.]

Murray, J.R., Roeloffs, E.A., Brooks, B.A., Langbein, J.O., Leith, W.S., Minson, S.E., Svarc, J.L., and Thatcher W.R., 2018, Leveraging geodetic data to reduce losses from earthquakes: U.S. Geological Survey Open-File Report 2018–1037, 34 p., accessed September 6, 2024, at https://doi.org/10.3133/ofr20181037.

National Earthquake Hazards Reduction Program [NEHRP], 2023, Strategic plan for the National Earthquake Hazards Reduction Program, fiscal years 2022–2029, April 2023: National Earthquake Hazards Reduction Program, 54 p., accessed July 22, 2024, at https://www.nehrp.gov/pdf/FY2022-29%20NEHRP%20Strategic%20Plan%20-%20Post%20Version.pdf.

Petersen, M.D., Shumway, A.M., Powers, P.M., Field, E.H., Moschetti, M.P., Jaiswal, K.S., Milner, K.R., Rezaeian, S., Frankel, A.D., Llenos, A.L., Michael, A.J., Altekruse, J.M., Ahdi, S.K., Withers, K.B., Mueller, C.S., Zeng, Y., Chase, R.E., Salditch, L.M., Luco, N., Rukstales, K.S., Herrick, J.A., Girot, D.L., Aagaard, B.T., Bender, A.M., Blanpied, M.L., Briggs, R.W., Boyd, O.S., Clayton, B.S., DuRoss, C.B., Evans, E.L., Haeussler, P.J., Hatem, A.E., Haynie, K.L., Hearn, E.H., Johnson, K.M., Kortum, Z.A., Kwong, N.S., Makdisi, A.J., Mason, H.B., McNamara, D.E., McPhillips, D.F., Okubo, P.G., Page, M.T., Pollitz, F.F., Rubinstein, J.L., Shaw, B.E., Shen, Z.-K., Shiro, B.R., Smith, J.A., Stephenson, W.J., Thompson, E.M., Thompson Jobe, J.A., Wirth, E.A., and Witter, R.C., 2024, The 2023 US 50-State National Seismic Hazard Model—Overview and implications: Earthquake Spectra, v. 40, no. 1, p. 5–88. [Also available at https://doi.org/10.1177/87552930231215428.]

Photograph showing U.S. Geological Survey and Turkish research scientists in Türkiye examining an odd uphill facing scarp that formed due to new movement at a very large preexisting landslide. Photograph by U.S. Geological Survey, continued on next page.

Poland, C., Bray, J.D., Johnson, L., Nikolaou, S., Rathje, E., and Sherrod, B., 2024, Plan to coordinate post-earthquake investigations supported by the National Earthquake Hazards Reduction Program (NEHRP): U.S. Geological Survey Circular 1542, 36 p., https://doi.org/10.3133/cir1542. [Supersedes USGS Circular 1242.]

Schmitt, R., Herman, M., Barnhart, W.D., Furlong, K., Benz, H.M., 2024, The 2023 Kahramanmaras, Turkey, earthquake sequence: U.S. Geological Survey story map, accessed July 22, 2024, at https://earthquake.usgs.gov/storymap/index-turkey2023.html.

Stern, L., Wood, K., Furlong, K., Yeck, W.L., and Benz, H.M., 2021, Seismotectonics of the eastern margin of the Australia Plate: U.S. Geological Survey story map, accessed July 22, 2024, at https://earthquake.usgs.gov/storymap/index-seismo-EasternMargin-AustraliaPlate.html.

U.S. Census Bureau, 2024, Construction spending: U.S. Census Bureau web page, accessed July 22, 2024, at https://www.census.gov/construction/c30/c30index.html.

U.S. General Services Administration, 2024, analytics.usa.gov: U.S. General Services Administration digital data, accessed September 29, 2024, at https://analytics.usa.gov/.

U.S. Geological Survey, 2017, Advanced National Seismic System—Current status, development opportunities, and priorities for 2017–2027: U.S. Geological Survey Circular 1429, 32 p., accessed September 6, 2024, at https://doi.org/10.3133/cir1429.

U.S. Geological Survey, 2021, U.S. Geological Survey 21st-Century Science Strategy 2020–2030: U.S. Geological Survey Circular 1476, 20 p., accessed September 6, 2024, at https://doi.org/10.3133/cir1476.

U.S. House of Representatives, 2023, Department of the Interior, Environment, and related agencies appropriations bill, 2024: U.S. Congress H.R. 118-155, 261 p., accessed September 6, 2024, at https://www.congress.gov/congressional-report/118th-congress/house-report/155/1.

U.S. Geological Survey geologists make measurements of fault rupture from the 2019 magnitude 7.1 Ridgecrest, California, earthquake. Photograph by Ben Brooks, U.S. Geological Survey, continued on next page.

For more information about this publication, contact:
Senior Science Advisor for Earthquake and Geologic Hazards,
Earthquake Hazards Program
U.S. Geological Survey
Mail Stop 905
12201 Sunrise Valley Drive
Reston, VA 20192
For additional information, visit: https://www.usgs.gov/programs/earthquake-hazards/
Publishing support provided by the
Reston, Rolla, and Tacoma Publishing Service Centers

Hayes and others—**U.S. Geological Survey Earthquake Hazards Program Decadal Science Strategy, 2024–33**—CIR 1544

ISSN 2330-5703 (online)
https://doi.org/10.3133/cir1544