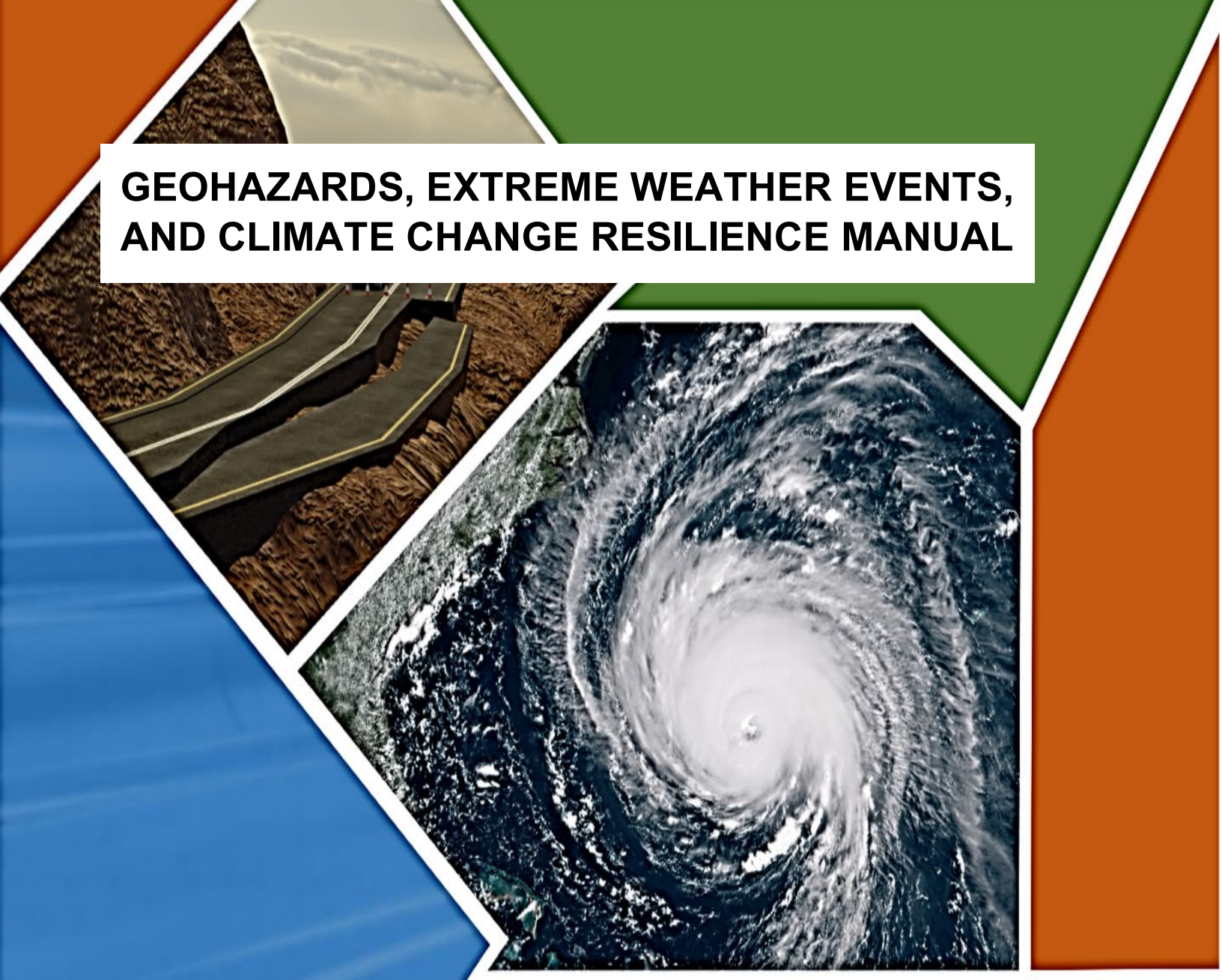
GEOHAZARDS, EXTREME WEATHER EVENTS, AND CLIMATE CHANGE RESILIENCE MANUAL



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FOREWORD

Geohazards such as landslides, liquefaction, rockfalls, subsidence, expansive/collapsible soils, and erosion can pose major threats to transportation assets. Other geologic hazards and extreme weather that affect transportation systems include but are not limited to rockfalls, wildfires, debris flows, mudflows, flooding, karst-related sinkholes, shoreline erosion, expansive soils, heaving bedrock, seismic activity, erosion, and dust storms.

Extreme weather events, warming temperatures, extreme cold weather, rising sea levels, and increased precipitation can contribute significantly to geohazards' frequency, severity, and intensity. For example, higher or more intense precipitation can make slope failures more likely. Rising temperatures may melt permafrost in Alaska, leading to differential surface settlements. Longer drought periods may cause more frequent wildfires, which reduce stabilizing vegetation and increase runoff and debris flows. Persistent cycles of drought can lead to aquifer drawdown and ground subsidence, as well as to changes in the shrink or swell potential of clay soils in certain regions. Sea level rise in coastal areas may lead to increasing groundwater levels, higher storm surges, and detrimental effects on existing transportation infrastructure.

Extreme weather events can also trigger or exacerbate geohazards. The increasing incidence of such events is a growing concern in certain regions of the United States. Geohazards can have a major impact on transportation systems. For example, the U.S. Geological Survey has estimated there are $2 billion to $4 billion in annual domestic losses and 25 to 50 deaths per year as a result of landslides.[1] In California alone, an average of 200 landslides and 10 related road closures occur each year along State highways (Turner et al. 2006).

A geohazards management program that evaluates associated risks on a transportation system can help agencies manage the threats and make comprehensive decisions related to system performance. Such a program can help agencies manage cost-effective methods for characterizing and reducing risk, develop adaptation methods, and establish a resilient transportation system.

The Federal Highway Administration (FHWA) conducted a literature review and peer exchange that informs a set of suggested practices for State transportation agencies to include when developing and maintaining a geohazard program. These practices include:

- Identifying and characterizing geohazards.
- Evaluating the severity, frequency, and intensity of geohazards influencing transportation function.
- Categorizing the influence of extreme weather events and climate change.
- Analyzing risk.
- Incorporating adaptation and resilience strategies to mitigate geohazard impacts to transportation systems.

[1] https://www.usgs.gov/faqs/how-many-deaths-result-landslides-each-year, accessed March 24, 2022.

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16. Abstract

Geohazards—such as landslides, liquefaction, rockfalls, subsidence, expansive/collapsible soils, and erosion—can pose major threats to transportation assets. Extreme weather events can also trigger and/or exacerbate geohazards, and the increasing incidence of such events is a concern in certain regions of the United States. A geohazards management program that evaluates the associated risk can help transportation agencies manage these threats by making comprehensive system performance decisions. Such a program can help agencies manage cost-effective methods for characterizing and reducing risk, develop adaptation methods, and establish a resilient transportation system.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	$candela/m^2$	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	$candela/m^2$	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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ACRONYMS AND ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ADAP	FHWA's Adaptation Decision-Making Assessment Process
AKDOT&PF	Alaska Department of Transportation & Public Facilities
CDOT	Colorado Department of Transportation
CGS	California Geological Survey
CSMIP	California Strong Motion Instrumentation Program
DOT	Department of Transportation
FHWA	Federal Highway Administration
FLMAs	Federal Land Management Agencies
GAM	geotechnical asset management
GCM	Global Climate Model
GHG	greenhouse gas
GIS	geographic information systems
GPS	global positioning system
InSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change
LIDAR	light detection and ranging tool
NCHRP	National Cooperative Highway Research Program
NOAA	National Oceanic and Atmospheric Administration
NPRA	Norwegian Public Roads Administration
NRC	National Research Council
ODOT	Oregon Department of Transportation
OMB	Office of Management and Budget
RCM	Regional Climate Model
TAM	Transportation asset management
TAMP	Transportation asset management plan
TEACR	Transportation Engineering Approaches to Climate Resiliency
TRB	Transportation Research Board
UAS	unmanned aerial systems
USGS	U.S. Geological Survey

EXECUTIVE SUMMARY

This technical manual was developed to assist State Departments of Transportation, Federal Land Management Agencies, and others in creating or improving geohazard programs. Geohazard programs can help agencies manage cost-effective methods for characterizing and reducing risk, including risks related to climate change and extreme weather events and their effects on transportation systems.

Geohazards such as landslides, liquefaction, subsidence, rockfalls, and erosion can pose major threats to transportation assets. Extreme weather events can trigger or exacerbate geohazards. The increasing incidence of such events is a growing potential concern.

Geohazard programs are an important tool in addressing the significant and growing risk presented by climate change (USDOT 2021). Because of the disproportionate impacts of climate change on vulnerable populations, addressing the risk of geohazards presented by climate change and extreme weather events can also be closely interlinked with advancing transportation equity (USDOT 2022).

As part of developing this manual, a literature review of national and international sources gathered information on the types and severity of geohazards, current management practices for geohazards affecting transportation systems, and links between geohazards and extreme weather events and climate resilience. Additionally, a peer exchange was conducted with experts on geohazards, climate, extreme weather events, environment, hydraulics, socioeconomics, and geotechnical asset management.

This manual provides a basic introduction to climate science and climate modeling. It explains briefly how the climate is changing; describes future scenarios, including an overview of climate models and downscaling of projections to the local scale; shares resources for obtaining climate model projections; and discusses future climate projection uncertainty. Examples are discussed from the FHWA Transportation Engineering Approaches to Climate Resiliency (TEACR) project—*Synthesis of Approaches for Addressing Resilience in Project Development*, referred to throughout as the TEACR "Synthesis Report" (2017). The report also discusses relevant case studies that focus on transportation assets.

The manual also discusses system-wide vulnerability analyses. This discussion shows how States can identify and inventory local geohazards, assess vulnerability of their transportation systems to geohazards, assess risk, and communicate this risk to decision makers and the public. Geotechnical assets also are discussed, along with how to assess individual assets using the Federal Highway Administration Adaptation Decision-Making Assessment Process tool. Information for selecting an adaptation or mitigation strategy is also presented.

Other topics include:

- Ongoing geotechnical asset management (GAM) efforts and their potential benefits for geohazard management.
- State and international transportation agencies' performance measurement procedures for geohazard programs.
- Information for agency professionals seeking to start or improve a geohazard program.

Finally, this manual identifies knowledge gaps in the practice. It suggests future research related to managing geohazards and to understanding the impact of changing climatic conditions and extreme weather events.

1 INTRODUCTION AND OVERVIEW

This manual provides technical information to assist State Departments of Transportation (DOTs), Federal Land Management Agencies (FLMAs), and other entities in developing or improving geohazard programs. This manual includes considerations for climate change and extreme weather events. This chapter describes the manual's purpose, primary references used, and organization.

1.1 Background

Geohazards such as landslides, liquefaction, subsidence, rockfalls, and erosion pose major threats to transportation assets. These geohazards are sometimes located outside the transportation corridor right-of-way but can still impact the transportation system. A geohazards management program can help transportation agencies evaluate risks, manage risks, and make comprehensive system performance decisions. A geohazards program can contribute to more resilient transportation systems and help agencies manage cost-effective methods for characterizing and reducing risk.

The U.S. Geological Survey (USGS) has estimated there are $2 billion to $4 billion in annual domestic losses and 25 to 50 deaths per year as a result of landslides.[2] In California alone, an average of 200 landslides and 10 related road closures were occurring each year along State highways in the early 2000s (Turner et al. 2006). One of the most expensive U.S. landslides in history, the 1983 landslide in Thistle, Utah, caused an estimated $400 million (current dollars) in damage to road and railroad infrastructure (Bouali et al. 2015; Turner et al. 2006). Material from a 2014 landslide in Oso, Washington, blocked approximately one mile of Highway 530 in Washington for two months, costing $150 million in damage repairs and causing the death of 43 people (Keaton et al. 2014b). In 2013 alone, Alaska spent $11 million repairing transportation infrastructure damaged from slumps, mudslides, and subsidence due to thawing permafrost (Connor and Harper 2013). These physical damage impacts have led to broader impacts to the transportation system in each State. The length of time that facilities were out of service demonstrates the importance of resiliency to the larger transportation network, the community, and the local economy.

Transportation systems also can be impacted by other geologic hazards and extreme weather events that cause geologic hazards. These include rockfalls, wildfires, debris flows, mudflows, flooding, karst-related sinkholes, shoreline erosion, expansive soils, heaving bedrock, seismic activity, erosion, and dust storms.

Extreme weather events, warming temperatures, and extreme cold weather can significantly impact the frequency, severity, and intensity of geohazards. Higher or more intense precipitation can lead to more slope failures. Rising temperatures that melt permafrost in Alaska lead to differential surface settlements. Longer droughts cause more frequent wildfires, which reduce stabilizing vegetation and increase runoff and debris flows. Persistent cycles of drought can also lead to aquifer drawdown, ground subsidence, and cracking (in clay soils). Sea level rise in

[2] https://www.usgs.gov/faqs/how-many-deaths-result-landslides-each-year, accessed March 24, 2022.

coastal areas, such as south Florida, may lead to increasing groundwater levels, higher storm surges, and detrimental effects on existing structures. Saturated soils resulting from sea level rise or changes in higher precipitation patterns and flooding can increase settlement of roadway embankments. Evaluating climate impacts involves both what has been observed in the past and how changing conditions may impact the public in the future.

Considering the significant risk of geologic hazards presented by climate change and extreme weather events, geohazard programs are increasingly important in helping transportation agencies to effectively address and reduce the risk, and establish more resilient transportation systems (USDOT 2021). In the transportation context, climate-related risk is many-faceted, including risks to the safety, mobility, effectiveness, equity, and the sustainability of the Nation's transportation infrastructure and the communities it serves. The U.S. Department of Transportation (USDOT or Department) intends to lead the way in addressing the climate crisis. (USDOT 2021; see also Executive Order 14008 on Tackling the Climate Crisis at Home and Abroad, 86 FR 7619 (2021))

In many cases, addressing the risk of geohazards presented by climate change and extreme weather events can also be closely interlinked with advancing transportation equity because of the disproportionate impacts of climate change on vulnerable populations, including older adults, children, low-income communities, and communities of color. Past Federal transportation investments have too often failed to consider transportation equity for all community members, including traditionally underserved and underrepresented populations (USDOT 2022). "Underserved populations" include minority and low-income populations but may also include many other demographic categories that face challenges engaging with the transportation process and receiving equitable benefits (see FHWA 2015). USDOT has committed to pursuing a comprehensive approach to advancing equity for all (USDOT 2022; see also Executive Order 13985, 86 FR 7009 [2021]). Equity in transportation seeks the consistent and systematic fair, just, and impartial treatment of all individuals, including individuals who belong to traditionally underserved communities or populations (USDOT 2022).

The FHWA encourages the advancement of projects that address climate change and sustainability (FHWA 2022). To enable this, FHWA encourages recipients to consider climate change and sustainability throughout the planning and project development process. A sustainable approach to highways means helping decision-makers make balanced choices among economic, social, and environmental values that will benefit current and future road users. For FHWA, a sustainable highway project satisfies basic social and economic needs, makes responsible use of natural resources, and maintains or improves the well-being of the environment.

State transportation agencies that develop geohazard management programs typically start by identifying their geohazards. The next step is to evaluate specific geohazards based on how they may affect the region's transportation assets. Evaluating risk and protecting transportation systems through mitigation measures can produce savings over the long term by avoiding substantial damage, cost, and time loss compared to the consequence costs of various events. Agencies that have established geohazards management programs, such as the Colorado

Department of Transportation and Alaska Department of Transportation and Public Facilities, say they have already seen financial and transportation asset management benefits.

1.2 Purpose

This manual provides technical information for developing and maintaining an effective geohazards program. Implementation of such a program can involve:

- Identifying and characterizing geohazards.
- Evaluating the expected severity, frequency, and intensity of geohazards influencing transportation functions.
- Identifying, categorizing, and evaluating the influence of extreme weather events and climate.
- Institutionalizing use of quantitative risk analysis and asset management best practices.
- Providing strategies to mitigate geohazard impacts to transportation systems.
- Utilizing adaptation measures to achieve a resilient transportation system.

Information is provided to help agencies integrate these efforts with geotechnical asset management systems and measured system performance, and account for socioeconomic factors in decision-making. This manual suggests an approach for including climate change concerns in geohazard programs. Suggested practices adhere to FHWA's overarching framework for addressing climate change vulnerabilities to the highway system, as described in the FHWA *Vulnerability Assessment and Adaptation Framework* report (FHWA-HEP-18-020). That resource is available on FHWA's website at: https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework.

1.3 Phase I: Literature Review

For Phase I of the manual development, a review was conducted of existing U.S. and international literature on the types and severity of geohazards; management practices for geohazards affecting transportation systems; and the link between geohazards and extreme weather events and climate change resilience.

The literature review identified the effects of climate change and extreme weather events on geohazards. It also identified knowledge gaps and possible future research areas. Suggested topics for research include developing practical methods for agencies to assess and manage geohazards; better understanding of the relationship between the triggering mechanisms of geohazards and climatic events or trends; and mapping high risk levels (such as maps showing high earthquake risk) from specific geohazards.

1.4 Phase II: Peer Exchange

A peer exchange was held during Phase II. For the meeting in Atlanta, Georgia (March 22 and 23, 2016), experts were invited from fields relating to various types of geohazards, climate change resilience, extreme weather events, environment, hydraulics, socioeconomics, and geotechnical asset management. Participants represented State and Federal transportation agencies, academia, and consulting firms. Attendees gave presentations and joined focused

breakout sessions on the current state of practice. They developed suggestions for managing geohazards that affect transportation systems while considering climate change and extreme weather events.

1.5 Elements of a Geohazards Program

Based on peer exchange discussion and the literature review, these elements should be considered in developing a geohazards program:

- Identifying the geohazards that pose the largest threats to the transportation system.
- Understanding the impact that climate change and extreme weather events may have on geohazards.
- Assessing vulnerability of assets and operations to geohazards.
- Assessing the potential benefits of geohazard mitigation measures.
- Improving geohazards risk planning to avoid cost and time impacts to transportation infrastructure and the public.
- Decreasing the overall geohazard-induced risk imposed to a transportation system.
- Continually reassessing and improving the program. Documenting and communicating this information across sectors and to the public.

Agencies should assess which aspects are most relevant and useful for their State or region.

1.5.1 System-Wide Vulnerability Analysis

Geohazard threats depend primarily on parameters determined by location, including geography, topography, and geology. Climate change and weather events can also influence threats. At a system-wide level, geohazard threats are frequently represented by maps or geographical information systems (GIS) to share data among different asset managers. This information typically comes from various sources: locations of past geohazard events, data produced by maintenance crews, topographical information, and State geological survey maps.

Geohazards affect not only physical transportation assets, but also operations and functions. For instance, closing one route could impact other routes and system capacity. Impacts can be magnified in urban settings. By mapping geohazards and how they may affect a transportation system, including operations and functions, an agency can identify high-risk areas to investigate further. Those who are involved in traffic operations also should be engaged.

The system's vulnerability should be established through a risk evaluation that includes experts on the geohazard and the affected transportation system. For instance, a bridge that is vulnerable to a landslide should be evaluated by both the structural engineer who is evaluating the bridge and the geotechnical engineer who is evaluating the landslide. Methods of analysis, including the Federal Emergency Management Agency's Hazus tool[3], are discussed further in Chapter 5, System-Wide Vulnerability Analyses for Geohazards.

[3] https://www.fema.gov/flood-maps/products-tools/hazus, accessed March 24, 2022.

1.5.2 Adaptation Analyses for Individual Assets

After a system-wide vulnerability analysis, individual assets with the greatest risk to a transportation system can be identified for adaptation. Protocols such as FHWA's Adaptation Decision-Making Assessment Process (ADAP) can be helpful in assessing adaptation response options, while considering the effects of future climate change scenarios, extreme weather events, and the uncertainties inherent in predictions. Long-term costs (repair, loss, economic, social) should be included in the evaluation.

1.5.3 Asset Management Systems

State transportation agencies have begun to implement transportation asset management (TAM) systems to manage bridges, pavements, and other assets. Geotechnical asset management (GAM) is a relatively recent strategy for managing and maintaining geotechnical assets. GAM is a body of management practices applied to geotechnical assets. GAM seeks to achieve and sustain a desired state of good repair over the lifecycle of the assets, at minimum practicable cost. Management of geotechnical assets—such as slopes, subgrades, embankments, or earth-retaining structures—includes continually evaluating geohazard-induced risk and deciding where and how to take mitigation measures. Geohazards directly or indirectly affect the performance of the network; therefore, it is suggested this assessment be included in the asset management plan.

1.5.4 Performance Measurement

The effectiveness of a geohazard program can be demonstrated through performance measures that identify areas for improvement. Performance measurement techniques depend on the agency but could include methods such as rating a corridor based on:

- road-user costs,
- likelihood that a hazard could occur,
- maintenance costs,
- safety,
- operational impacts, and
- social considerations.

The change in corridor ratings over time, if applied effectively, can identify and quantify the effectiveness and cost savings from a geohazards program. Setting targets for performance measurement may be difficult; however, such targets can greatly impact network performance. Geohazards may be evaluated during the "performance gap analysis" for the asset management plan.

1.5.5 Public Communications

Geohazard programs typically are better understood, more sustainable, and more effective with a high level of public awareness and support. Public communications can be accomplished by various methods: social media, public presentations, pamphlets, testing of geohazards alert systems, workshops in critical areas, online technical webinars, and conferences on geohazards in areas of concern. Other ways to reach the public include hazard warning systems and signed evacuation routes for hurricanes, tornadoes, and tsunamis; signals triggering when landslide movement exceeds a threshold to stop traffic; and signs for falling rocks. Interactive maps

(already developed for earthquakes, rainfall, traffic, and wildfires) can be posted on public websites. These methods of communication can also inform decision makers involved in funding geohazard programs.

1.6 Organization of Manual

The remainder of this manual is organized as follows:

- *Chapter 2: Terms and List of Transportation Geohazards.* This chapter provides key terms used throughout this manual such as "geotechnical asset," "extreme weather event," "risk," and "geohazard." Geohazards identified in this manual are also listed.
- *Chapter 3: Sensitivity of Geohazards to Extreme Weather Events and Climate Stressors.* This chapter provides information on the current understanding of the link between geohazards and climate change, extreme events, and extreme weather events. Weather and non-weather-related triggering factors are identified for geohazards covered in this manual.
- *Chapter 4: Understanding Climate Change and Climate Projections.* This chapter presents a summary of climate change and climate projections.
- *Chapter 5: System-Wide Vulnerability Analyses for Geohazards.* This chapter provides practices and examples for identifying and inventorying geohazards within a State, assessing vulnerability of transportation systems to geohazards, assessing risks, and communicating this risk to decision makers and the public.
- *Chapter 6: Adaptation Assessments for Individual Geotechnical Assets*. This chapter outlines the process for assessing an individual asset using FHWA's Adaptation Decision-Making Assessment Process (ADAP) tool and deciding when to mitigate. Methods for selecting an adaptation or mitigation strategy are also presented.
- *Chapter 7: Use of Geotechnical Asset Management in Geohazard Programs*. This chapter discusses geotechnical asset management (GAM) efforts and their potential benefits for avoiding or mitigating geohazard impacts on the transportation system.
- *Chapter 8: Performance Measurement for Geohazard Programs—Example Practices*. This chapter identifies performance management procedures that State agencies and international transportation agencies have used.
- *Chapter 9: Communicating Transportation Geohazards*. This chapter provides information on using socioeconomics to communicate transportation geohazards to the public and decision makers.
- *Chapter 10: Establishing Geohazards Management Techniques.* This chapter provides information for transportation agencies seeking to start or improve a geohazard program, including suggested short-term and long-term goals.
- *Chapter 11: Identification of Gaps and Research Needs.* This chapter discusses knowledge gaps in the current practice for transportation geohazards and climate change resilience and suggests future research topics.
- *References.*

2 TERMS AND LIST OF TRANSPORTATION GEOHAZARDS

Table 2-1 provides basic descriptions of terms used throughout this manual. Table 2-2 lists geohazards referred to in this manual. The list of geohazards is not exhaustive but includes geohazards commonly encountered that have potential to damage transportation facilities.

Table 2-1: Description of Terms

Term	Description	Source
Adaptation	Adjustment in natural or human systems in anticipation of a changing environment in a way that effectively uses beneficial opportunities or reduces negative effects.	TEACR Synthesis Report (FHWA-HEP-17-082)
Adaptation Decision-Making Assessment Process (ADAP)	A refined version of the 11-step General Process for Transportation Asset Adaptation Assessments that FHWA developed for the U.S. DOT Gulf Coast Phase 2 project. A framework for conducting adaptation assessments of individual facilities.	TEACR Synthesis Report
Asset management	A body of management practices, also known as transportation asset management (TAM), applied to infrastructure. Asset management seeks to achieve and sustain a desired state of good repair over the lifecycle of the assets at minimum practicable cost.	TEACR Synthesis Report
Climate change	Refers to significant long-term changes in climate metrics. Includes major variations in temperature, precipitation, or wind patterns, among other environmental conditions that occur over several decades or longer. Changes in climate may manifest as a rise in sea level or in increased frequency and magnitude of extreme weather events.	TEACR Synthesis Report
Climate models	Complex numerical models used to examine the interactions between the atmosphere, land surface, oceans, and sea ice—and to estimate future climate change. Also known as Global Climate Models (GCMs) and Regional Climate Models (RCMs).	TEACR Synthesis Report
Climate scenarios	Plausible futures that are built on different trajectories of future greenhouse gas concentrations, land use, and other factors are then run through climate models to project future values of temperature and precipitation.	TEACR Synthesis Report
Climate metric	Parameters used to measure and describe climate. For example, temperatures, precipitation, wind, storm surge, waves, and relative sea level change.	TEACR Synthesis Report
Downscaling	A process or procedure for increasing the spatial resolution of climate model outputs.	TEACR Synthesis Report

Term	Description	Source
Emission scenarios	Plausible future greenhouse gas emissions trajectories that are based on a range of potential factors, such as economic growth, population change, and energy consumption. These factors are translated into emissions and concentrations of GHG over time.	TEACR Synthesis Report
Exposure	The nature and degree to which a system or asset is exposed to significant climate variations.	TEACR Synthesis Report
Extreme event	A severe and rare natural occurrence that may pose significant potential for damage, destruction, or loss of life.	HEC-17 2nd Edition (FHWA-HIF-16-18)
Extreme weather event	Significant anomalies in temperature, precipitation, and winds that may manifest as heavy precipitation and flooding, heatwaves, drought, wildfires, and windstorms. They are weather-induced events that occur rarely, yet usually cause damage, destruction, or severe economic loss.	HEC-17 2nd Edition
Geohazard	Natural hazard governed by geological features and environmental conditions that has the potential to lead to damage of transportation assets, loss of life, or economic losses.	–
Geotechnical asset	A geotechnical infrastructure component that adds value to a highway agency and contributes to the performance of a transportation corridor. It may include a slope, embankment, subgrade, or earth-retaining structure. It may also include a geotechnical element of other managed assets such as bridges, tunnels, pavements, and culverts.	Anderson et al. (2017)
Hazard	Event or condition that has the potential to cause damage or loss to transportation systems.	–
Lifecycle costs	Initial capital outlays plus costs of long-term management, including materials and labor, as well as traffic disruption.	TEACR Synthesis Report
Resilience	With respect to a project, "resilience" means a project with the ability to anticipate, prepare for, and/or adapt to changing conditions and/or withstand, respond to, and/or recover rapidly from disruptions, including the ability: (A) to resist hazards or withstand impacts from weather events and natural disasters, or reduce the magnitude or duration of impacts of a disruptive weather event or natural disaster on a project; and (B) to have the absorptive capacity, adaptive capacity, and recoverability to decrease project vulnerability to weather events or other natural disasters.	23 U.S.C. § 101(a)(24)[4] (See also definition in TEACR Synthesis Report)

[4] Added by Sec. 11103 of the Bipartisan Infrastructure Law, enacted as the Infrastructure Investment and Jobs Act, Pub. L. 117-58 (Nov. 15, 2021)). *See also* FHWA Order 5520 (FHWA 2014).

Term	Description	Source
Risk	Quantitative measure of threat or hazard, often represented as probability or likelihood of occurrence of hazardous events or trends multiplied by the consequence if these events or trends occur.	TEACR Synthesis Report
Vulnerability	The extent to which a transportation asset is susceptible to sustaining damage from hazards (including climatic). Vulnerability is a function of exposure, sensitivity, and adaptive capacity.	TEACR Synthesis Report
Weather	The meteorological and atmospheric conditions at a particular place and time, including temperature, precipitation, wind, etc. Weather represents conditions over a short period of time; climate, meanwhile, represents conditions over longer periods.	TEACR Synthesis Report

Table 2-2: List of Geohazards

Geohazard	Description	Source
Coastal erosion/ cliff retreat	Erosion of soil or rock from beaches, dunes, or cliffs due to wave action, tidal currents, or wave currents.	–
Debris flows/ earthflows/ mudflows	Rapid downhill movement of earth materials that may contain a combination of materials, such as soil, ash, air, rock, water, and organic matter. Liquefied fine-grained material that runs downhill and flows easily and quickly.	USGS: Highland (2013)
Dust storms	Windstorms that transport fine soil particles in the air.	–
Earth fissures	Deep cracks in the earth associated with groundwater withdrawal that propagate to the surface. These cracks may extend several hundred feet deep, several miles long and several feet wide	AZ Geological Survey
Expansive soils	Soils that have the potential to absorb large amounts of water, resulting in shrinking and swelling with changing moisture conditions.	–
Karst features	Features associated with a type of topography that is formed over limestone, dolomite, or gypsum by dissolution. It is characterized by sinkholes, caves, and underground drainage.	USGS
Landslides	Mass downward movement of soil or rock with a distinct failure surface	USGS: Highland (2013)
Liquefaction	Loss of strength of saturated or partially saturated, loose soil due to increased pore water pressure generally from earthquakes, causing it to behave like a liquid.	–
Permafrost	Subsurface layers of permanently frozen soil.	–
Rockfalls/topples	Abrupt detachments of rock from steep slopes. Falls are often associated with weathering from water in rock fractures and joints.	USGS: Highland (2013)
Scour	Erosion of streambed or bank material around a foundation element due to flowing water; often considered as being localized.	HEC-18 (FHWA-HIF-12-003)
Seismic-induced ground shaking	Shaking of the ground surface originating from tectonic, volcanic, or blasting activity within the earth.	FHWA 2012 (FHWA-HIF-12-003)
Seismic-induced lateral spread and permanent ground deformation	Extension and/or flow of liquefied and overlying intact (non-liquefied) material due to earthquakes. Surface fault rupture due to earthquakes.	–
Settlement/subsidence	Downward movement of ground surface as a result of various processes, including consolidation, densification, subsurface erosion, and extraction of subsurface fluids.	–
Slope erosion	Erosion of soil or rock from existing slopes primarily due to precipitation, freezing, and thawing.	USGS: Highland (2013)

3 SENSITIVITY OF GEOHAZARDS TO EXTREME WEATHER EVENTS AND CLIMATE STRESSORS

Geohazards such as landslides, rockfalls, erosion, and subsidence can be triggered or exacerbated by extreme weather events and climatic factors, including higher temperatures, droughts, increased rainfall, and more frequent and stronger windstorms. The impact of these geohazards on a transportation system can lead to property damage, economic losses, and even loss of life. The causal relationship between frequency and intensity of geohazards, climate change, and extreme weather events is complex, characterized by many uncertainties. Establishing this relationship involves making many assumptions. Identifying the potential for increased impacts on transportation systems can be challenging.

Transportation agencies developing a geohazard program can benefit from a better understanding of the impact of climate change on geohazards. Agencies also can benefit from climate metrics, such as soil moisture data, that can be translated to analyses of geohazard risk.

The Transportation Engineering Approaches to Climate Resiliency (TEACR) project—*Synthesis of Approaches for Addressing Resilience in Project Development* (2017) report and supporting asset/facility analyses—provide examples of climate change impacts for geohazards. These examples include temperature and precipitation impacts to pavements on expansive soils, temperature and precipitation impacts on rock and soil slope stability, protection of a roadway during a storm surge, and debris flows caused by rain events following wildfires.

3.1 Climate Change Impacts for Geohazards—Examples from the TEACR Project

The TEACR report discusses the process for addressing resilience in project development. The report draws from a range of engineering-focused case studies to examine the impact of climate stressors, or triggering factors, on transportation assets. The report also presents lessons learned, project-level adaptation options, and knowledge gaps identified from the case studies. A few examples of the impacts of climate change and extreme events on geotechnical assets and geohazards in specific locations, based on the TEACR study, are described below (FHWA 2017c).

3.1.1 Temperature and Precipitation Impacts to Pavements on Expansive Soils

One case study examined the effects of temperature and precipitation change on expansive soils in the subgrade of State Highway 1–70 near Dallas, Texas. Expansive soils are clays that absorb water and increase in volume. Expansive soils swell with increased moisture and shrink with decreased moisture. Declining water tables, drought, or heat waves could result in subsidence

and cracking of expansive soils, while sustained precipitation could result in the swelling of expansive soils. Figure 3-1 shows an example of expansive soil damaging a pavement structure.

Figure 3-1: Effects of expansive soils on pavements.

Source: Texas Department of Transportation

According to the TEACR Pavement Shrink-Swell study (FHWA 2017d), climate change projections in the Dallas-Fort Worth area include a steady increase in temperature and drier ambient and subgrade conditions. Drier subgrade conditions will lead to a higher potential for soil swelling rather than shrinking. However, drier conditions will lead to a lower equilibrium moisture content and thus more shrinking than swelling, as noted in the study. The TEACR Pavement Shrink-Swell study concluded that higher air temperatures increase pavement cracking and distress, which would call for higher quality asphalt binders. Increased aridity also may lead to lateral vegetation growth with roots penetrating the subgrade and overlying pavement, causing cracks and uneven surfaces.

3.1.2 Precipitation and Temperature Impacts on Rock and Soil Slope Stability

Figure 3-2: Soil slope along Virginia I-77.

Source: Virginia Department of Transportation

A TEACR Slope Stability study evaluated the potential impacts of projected changes in precipitation, temperature, and freeze-thaw cycles on slope stability for a soil slope and rock slope from milepost 1.8 to 6.3 on I–77 in Carroll County, Virginia.

For soil slopes, higher precipitation could lead to increased pore water pressure (if the soil is saturated) and higher total unit weight, which can increase the driving forces of a slope (FHWA 2018f). For the slope shown in Figure 3-2, a parametric analysis was performed by varying one of the key contributors to slope failure: the groundwater level. This allowed the analysis to capture the potential effects of increased precipitation. In this case, the higher groundwater elevation did not have

a significant impact on the probability of the existing slope failing; extensive climate modeling was not considered necessary.

For rock slopes along I–77, freeze-thaw cycles were considered because these cycles can accelerate the weathering of rocks into soil. A higher frequency of freeze-thaw cycles could speed up the rate at which rocks weather and could increase the occurrence of rockfalls. If the number of freeze-thaw cycles were to decrease, rockfall events may become less frequent.

In this case study, climate change projections were used to count the number of days in a year the temperature range included values above and below 32 degrees Fahrenheit (freezing threshold). The study concluded that future freeze-thaw events, obtained from climate projections, would occur from 14 to 50 percent less frequently than historic conditions, due to warmer future temperatures. Therefore, no significant increase in rockfalls due to climate change, specifically freeze-thaw cycles, is expected for this section of I–77.

3.1.3 Roadway Impacts from Storm Surge Related to Sea Level Rise

As part of the TEACR Roadway Surge study, a 3.5-mile section of U.S. Highway 98 that runs parallel to the Gulf of Mexico in Okaloosa County, Florida, was assessed for climate stressors. This study examined the cost-effectiveness of mitigation measures already performed to protect the highway. Figure 3-3 shows erosion damage to Highway 98 that occurred during a tropical storm in 2005. Adaptation included a buried 18-foot deep sheet pile wall, the top of which is visible in Figure 3-4, and a buried gabion mattress.

Figure 3-3: Damage to U.S. Highway 98 in 2005 due to a tropical storm (Okaloosa County, Florida).

Source: Florida Department of Transportation.

Figure 3-4: Protection of U.S. Highway 98 includes a buried 18-foot deep sheet pile wall and buried gabion mattress.

Source: Florida Department of Transportation.

In this study, the effectiveness of adaptation measures was assessed for current climate conditions, projected sea level rise, and increased storm surge. The study showed that the economic value of adaptation becomes much stronger with sea level rise considerations.

3.1.4 Debris Flows from Wildfires

Another case study considered the impacts of increased high intensity precipitation and wildfires (from higher temperatures and droughts) on the occurrence of debris flows in John Day, Oregon. A channel formed in a post-wildfire debris flow that had filled an existing streambed, as shown in Figure 3-5. The TEACR Culvert study (FHWA 2017f) found that the anticipated increase in wildfires and droughts, and subsequent loss of stabilizing vegetation, would significantly impact the accumulation of debris and amount of runoff to a nearby culvert crossing under a roadway. Higher runoff and debris flows would clog and reduce the capacity of the culvert more often, leading to more frequent overtopping of the roadway.

Figure 3-5: Post-wildfire channel for debris flow in John Day, Oregon.

Source: FHWA 2017f.

3.2 General Impacts of Climate Change and Extreme Weather Events on Geohazards

Examples of trends identified in current research on projected climate and weather events and the occurrence of geohazards are:

- Most shallow slope failures and landslides occur during intense or prolonged rainfall (Collin et al. 2008). For deeper landslides, it takes time for increased precipitation to infiltrate to depth and reduce stability. For regions with projected higher winter precipitation and precipitation intensity, frequency of both deep and shallow landslides can be expected to increase (Jaedicke et al. 2009).
- With rising temperatures in some areas currently experiencing snowfall, precipitation is more likely to fall as rain rather than snow. More intense floods and rain precipitation could lead to slope erosion and earthflows (Chi et al. 2011).
- Longer and hotter heat waves and droughts in the western United States could lead to cracking of soil, which could trigger slope failures because strength would be lost on the plane of the crack. These cracks could also fill with water during projected heavy rainfalls, increasing water pressure and overloading slopes. Water-filled tension cracks are already a major trigger for slope failures, and climate scenarios project exacerbation of these conditions (Duncan and Wright 2005; Meyer et al. 2014).
- In regions like Alaska, thawing permafrost could result in less stable soil, subsidence, and landslides (Olsen et al. 2015).

- Extreme temperature fluctuations and freeze-thaw cycles can weaken soil and rock masses and increase susceptibility to slope failures (Highland 2013).
- Rapid snowmelt also has the potential to trigger landslides, as water flows down and infiltrates slopes (Collin et al. 2008).
- Temperature fluctuation does not appear to influence timing of rockfalls. However, more ice-wedging failures occur in fractured rock masses than in intact rock masses (Occhiena and Pirulli 2012).
- It is not likely that climate change will impact the frequency or magnitude of earthquakes. However, there are studies suggesting a link between man-made climate change and increased seismic events (McGuire 2012).
- Drier conditions in the Southwest will contribute to more earth fissures forming. Rainstorms can quickly erode walls of fissures, forming gullies 5- to 15-feet wide and tens of feet deep (Arizona Geological Survey 2015a).
- Droughts and heat waves in the western United States, combined with occasional sustained periods of precipitation, would increase shrinking and swelling of expansive soils, increasing the potential for damage from subsidence and cracking (Arizona Geological Survey 2015b).
- Projected increases in sea level rise and hurricane intensity will likely lead to more coastal erosion, due to the combined effect of more water and higher storm surge. It will likely lead to more drainage problems as well. Studies of the major U.S. hurricanes in 2017 in Texas, Florida, and Puerto Rico, as well as studies of Superstorm Sandy in 2012 and recent hurricanes, may provide useful information and perhaps dramatic examples of these impacts.
- Droughts are projected to increase due to climate change, resulting in more wildfires as vegetation weakens, soils dry, and temperatures increase. Wildfires result in less stabilizing vegetation and less permeable soil. It is estimated that erosion rates and runoff are 1 to 3 times higher after wildfires and mudflows, and debris flows are common post-wildfires. Areas damaged by wildfires with increased runoff and sediments entering rivers could also increase embankment erosion and scour (Smith and Bhatia 2015; Keaton et al. 2014a).
- Wind erosion and dust storm frequency is also likely to increase in the southwestern United States, as soils become drier with increased temperatures and less overall precipitation (Olsen et al. 2015).

Table 3-1 presents a list of geohazards, with examples of both non-weather- and weather-related triggering factors, or stressors, as applicable. Other factors that trigger geohazard events are not weather-related. The I–82 landslide due to nearby mining activities and I–70 sinkholes due to land development are examples of non-weather-related geohazards. Climate metrics that could be used to assess the impact on geohazards are provided for linking available information from climate models to parameters relevant to a geohazard analysis.

Table 3-1: Geohazards and Triggering Factors

Geohazard	Examples of Non-Weather-Related Triggering Factors	Examples of Weather-Related Triggering Factors	Climate Metric Example
RELATED TO SLOPE STABILITY			
Landslides	• Excavation at the toe of the slope (decreasing stability) • Poor maintenance of slope drainage systems	• Increased groundwater level from sustained precipitation, intense precipitation, antecedent moisture • Increased soil moisture and saturation • Wet/dry cycling, desiccation, cracking, and general deterioration	• Max 60-day rainfall
Rockfalls/Topples	• Blasting during construction that dislodges rock pieces	• Cycles of freeze-thaw that continually increase rock fractures	• Number of freeze-thaw cycles per year • Max 24-hour precipitation
Debris Flows/Slope Erosion	• Poor drainage design of a slope	• Increased wildfires leave slopes more prone to erosion • High intensity rainfall	• 96-hour storm (it rains lightly for 3 days and then there is a 50-year 24-hour rainfall)—e.g., City of Los Angeles, CA • Wildfire projections
Earthflows/Mudflows	• Poor drainage design of a slope • Geometry of slope	• High intensity rainfall	• 96-hour storm (it rains lightly for 3 days and then there is a 50-year 24-hour rainfall)—e.g., City of Los Angeles, CA
RELATED TO PROBLEMATIC SOIL AND ROCK CONDITIONS			
Settlement/ Subsidence	• Groundwater extraction • Oil and gas extraction	• Droughts leading to a lower groundwater level	• Annual/seasonal precipitation

Geohazard	Examples of Non-Weather-Related Triggering Factors	Examples of Weather-Related Triggering Factors	Climate Metric Example
Karst Features and Underground Mines	• Manmade underground mines that can collapse • Changes in surface/ groundwater chemistry that might influence dissolution rates	• Increased flow of water underground	• Annual precipitation • Cyclic periods of increased precipitation/recharge preceded by lower than normal groundwater conditions
Earth Fissures	• Groundwater extraction	• Droughts leading to a lower groundwater level	• Average annual temperature • Annual precipitation
Expansive Soils	• Poor drainage design	• Extreme wet/dry cycles • Increased temperatures	• Average annual temperature • Precipitation measurements
Permafrost Thawing	• Heat sources from underground utilities or facilities	• Increased temperatures over a long period of time	• Daily temperature projections
RELATED TO EROSION (EXCLUDING SLOPE EROSION WHICH IS INCLUDED IN SLOPE STABILITY GEOHAZARDS)			
Dust Storms	• Poor farming practices • Soil moisture	• Drought • High speed winds	• Max windstorm speed • Average annual/seasonal temperature and precipitation
Coastal Erosion/Cliff Retreat	• N/A	• Wave action • Storm surges • Tidal currents	• Expected sea level rise • Max storm surge
Scour	• Poor hydraulic design of bridge foundations such as inadequate countermeasures	• High rainfall during storm increasing flow volume and velocity • Maximum flood flow	• Max 24-hour precipitation • Multi-day or weekly maximum precipitation
RELATED TO SEISMIC ACTIVITY			
Seismic-Induced Ground Shaking	• Earthquakes • Blasting	• N/A	• N/A

Geohazard	Examples of Non-Weather-Related Triggering Factors	Examples of Weather-Related Triggering Factors	Climate Metric Example
Liquefaction	• Earthquakes • Blasting	• Rising groundwater table saturating a loose sand; increasing liquefaction potential • Increased sea level rise	• Max 60-day rainfall • Increased sea level rise
Seismic-Induced Lateral Spread and Surface Rupture	• Earthquakes • Blasting • Fracking	• Rising groundwater table saturating a soil; increasing potential for lateral spread	• Max 60-day rainfall

4 UNDERSTANDING CLIMATE CHANGE AND CLIMATE PROJECTIONS

Changes in weather-related metrics (listed in Table 3-1) could lead to increasing frequency and severity of geohazards.

This chapter provides an introduction to climate change science and climate modeling. It describes future climate scenarios, then provides an overview of climate models and downscaling. The chapter provides information on where climate model projections can be obtained and concludes with a discussion of uncertainty in climate projections.

The FHWA recognizes that the United States has a "once in a generation" opportunity (USDOT Climate Action Plan, August 2021) to address the risks climate change presents to the safety, effectiveness, equity and sustainability of the Nation's transportation infrastructure and the people it serves. Mitigating these risks is in line with the Biden-Harris Administration's Executive Order on Tackling the Climate Crisis at Home and Abroad (EO 14008; January 27, 2021), which envisions a new American infrastructure and clean energy economy.

4.1 Causes of Climate Change

The sun warms and provides energy to the earth. Sunlight is either absorbed or reflected by the earth and the atmosphere. The concentrations, or level, of greenhouse gases (GHGs) in the atmosphere controls how much of the resulting heat is lost to space or retained (USGCRP 2017, USEPA[a]). Higher greenhouse gas concentrations lead to higher global temperatures, sea level rise and changes in precipitation patterns.

GHGs include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and synthetic fluorinated gases (perfluorocarbons [PFCs], hydrofluorocarbons [HFCs], sulfur hexafluoride [SF_6], chlorofluorocarbons [CFCs], and hydrochlorofluorocarbons [HCFCs]). Water vapor is by far the most prevalent GHG, but its concentrations are minimally influenced by humans. The remaining GHGs are influenced by human activity. Of these, the total mass of CO_2 has by far the largest warming potential (or forcing) followed by CH_4 and the gases regulated by the Montreal Protocol (CFCs and HFCs). (USGCRP 2017, USEPA[a])

The concentration of GHGs in the atmosphere has increased due to human activity since the start of the Industrial Revolution (the late 1700s). The higher quantities of GHGs are a result of increased burning of fossil fuels and other industrial processes. Expanding agricultural activities to feed a growing global population have also contributed by increasing the quantity of methane and nitrous oxide emitted. Annual GHG emissions have increased steadily with population growth and industrialization, with especially sharp increases occurring in recent years. Figure 4-1 shows how the concentrations of CO_2 (the primary greenhouse gas of concern) have increased over the last four decades.

Once GHGs are released into the atmosphere, they remain there for anywhere from a few years to hundreds of years, depending on the gas. Past GHG emissions, particularly of CO_2, are projected to continue to cause warming many years into the future until they are removed by natural or other processes. (USEPA[b])

CO_2 accounted for roughly two-thirds (66.1 percent) of major long-lived greenhouse gases in 2019 measured in terms of radiative forcing, followed by 16.4 percent for methane, 5.1 percent for CFC12, 1.8 percent for CFC-11, and 4.1 percent attributed to other gases (USEPA[c]).

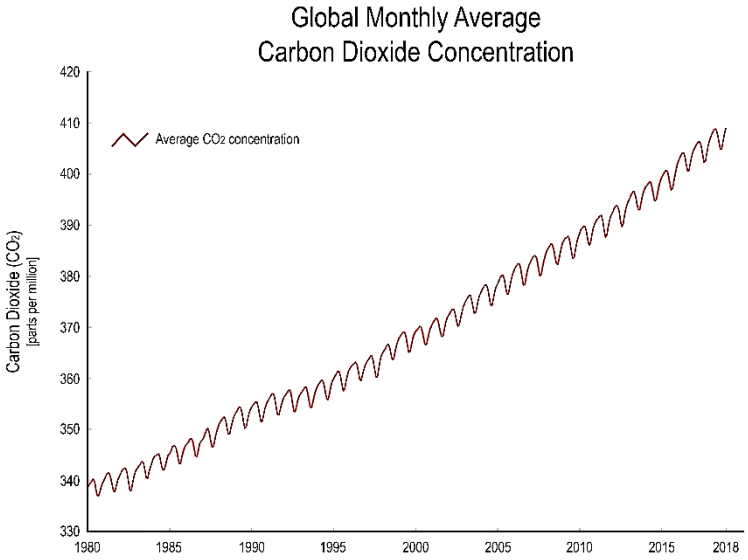

Figure 4-1: Global monthly average carbon dioxide concentration.

Note: The amount of CO_2 in the atmosphere increased more than 20 percent in less than 40 years, owing largely to human activities, and representing well over 50 percent of the total increase in atmospheric carbon dioxide since the onset of the Industrial Revolution (1750). Source: Jim Butler, NOAA, cited in 2019, *Trends in Atmospheric Carbon Dioxide, Earth System Research Laboratory*. [Available online at https://www.esrl.noaa.gov/gmd/ccgg/trends/gl_full.html; cited in: https://www.globalchange.gov/browse/indicator-details/3653]

Increasing atmospheric GHGs cause a cascading series of impacts to the Earth's climate system, many of which can affect geohazards. Most fundamentally, more GHGs lead to warmer average surface temperatures (with greater changes toward the poles), a trend that is being observed around much of the world (Intergovernmental Panel on Climate Change [IPCC] 2013). In permafrost regions, this can lead to thawing of the frozen soil which, in addition to causing profound thaw settlement concerns for infrastructure, releases stored GHGs that may contribute to further warming.

Because a warmer atmosphere can hold more water vapor—which is a positive feedback to more warming because water vapor is a GHG—more intense precipitation events may occur. This trend is being observed around the world (IPCC 2013). Intense precipitation events can lead to changes in landslide and debris flow frequency and severity, as well as affect groundwater tables. Conversely, warmer temperatures can lead to more evaporation and contribute to drought conditions and declines in the level of the groundwater table.

Thus, there is a tendency toward greater extremes in a warming world, especially with respect to precipitation, which has implications for many geohazards. For example, a location could be

subject to more extreme precipitation events *and* more severe droughts. The frequency and timing of such extreme events would continue to be shaped by day-to-day weather patterns, but the patterns themselves may change due to a complex interplay of atmospheric dynamics. The effects of warming on broader weather patterns remains an active area of scientific research.

Planetary warming also has implications for global sea levels. As water warms, it expands. Thus, as temperatures rise due to climate change, sea levels are projected to also rise due to the thermal expansion of the oceans. Warming is expected to also accelerate the melting of land-based glaciers and ice sheets, a trend already documented in many regions of the world. The resulting higher sea levels could have implications for coastal erosion and near-shore groundwater tables in many coastal areas.

4.2 Future Climate Scenarios

Scientists use scenarios to help project the possible future range of GHG emissions and concentrations and uncertainty in the projections. Scientists also assess the implications of the scenarios through modeling (IPCC 2013). The scenarios indicate different potential trajectories for atmospheric GHG concentrations over the remainder of the 21st century and beyond, and resulting changes in the climate. There are many different possible storylines that could bring about each GHG pathway. (Similar, more recent scenarios—"Shared Socioeconomic Pathways (SSPs)"— have also been developed and are discussed in the IPCC's 6th Assessment Reports.) (IPCC 2021)

Climate scientists have developed four RCPs (Representative Concentration Pathways) as part of the Coupled Model Intercomparison Project (CMIP) climate projections, listed below from low to high, by level of GHG emissions assumed (USGCRP 2017).

- **RCP 2.6:** This scenario assumes a significant reduction in GHG concentrations by the middle of the 21st century. Many experts believe that it may be too optimistic to achieve this scenario given current GHG emission trajectories and the technological and policy challenges with reducing emissions.
- **RCP 4.5:** Under this scenario, GHG concentrations increase at a lower rate in the near-term (compared with current trends). Concentrations then stabilize later in the century, around 2070.
- **RCP 6.0:** In this scenario, the rate of increase in GHG concentrations slows in the near-term but does not fully stabilize until around 2100.
- **RCP 8.5:** In this scenario, the most pessimistic scenario developed by scientists, GHG concentrations continue rising unabated on their current trajectory with no stabilization through 2100.

Figure 4-2 shows the warming potential of each RCP over the 21st century. There is no way to quantify the probability that any particular emission scenario will occur because of the uncertainty discussed above. The USGCRP 2017 report indicated that there is an equal likelihood that each may occur although there is increasing acceptance that RCP 2.6 is likely to be overly optimistic.

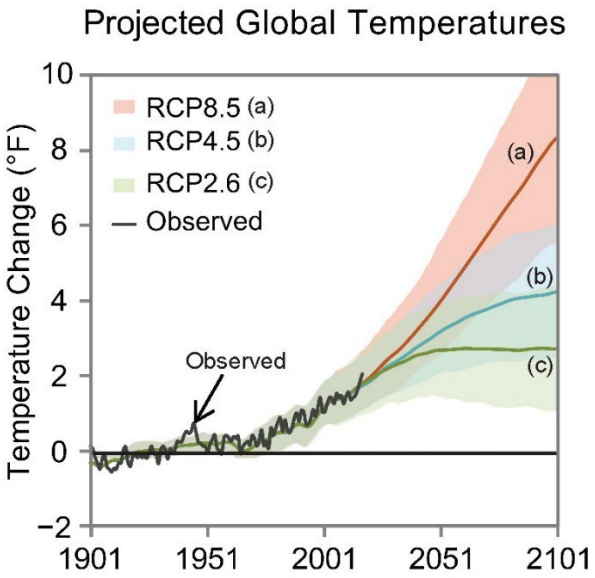

Figure 4-2: Projected changes in global annual mean surface temperature for various RCPs relative to a 1901–1960 baseline.

Source: USGCRP 2017.

Note: In Figure 4-2, the multimodel simulated time series 1900–2100 for the change in global annual mean surface temperature is relative to 1901–1960 for a range of the RCPs (Representative Concentration Pathways). These scenarios account for the uncertainty in future emissions from human activities (as analyzed with the 20-plus models from around the world used in the most recent international assessment). The mean (represented by solid lines) and associated uncertainties (represented by shading, showing ±2 standard deviations [5 percent to 95 percent] across the distribution of individual models based on the average over 2081–2100) are given for all of the RCP scenarios. The numbers of models used to calculate the multimodel means are indicated. (From *Climate Science, Special Report: The Fourth National Climate Assessment: Volume 1*, adapted from Walsh, J. et al., 2014: Chapter 2: "Our Changing Climate." *Climate Change Impacts in the United States: The Third National Climate Assessment.* Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program.)

Global sea level rise projections have also been developed by research organizations, including the National Oceanic and Atmospheric Administration (NOAA), the U.S. Army Corps of Engineers (USACE), and the National Research Council (NRC).

Figure 4-3 shows trends for a range of projections. The variability among the data sources and scenarios is attributable to assumptions on the amount of thermal expansion (which depends on how much warming occurs, per the RCPs) and different assumptions about glacial melt processes, etc. Note that values shown in Figure 4-3 are global means and the amount of change projected for any given location, relative sea level, should include vertical land movement and other local factors if known. Section 4.4 below includes links to more information on the data sources for Figure 4-3.

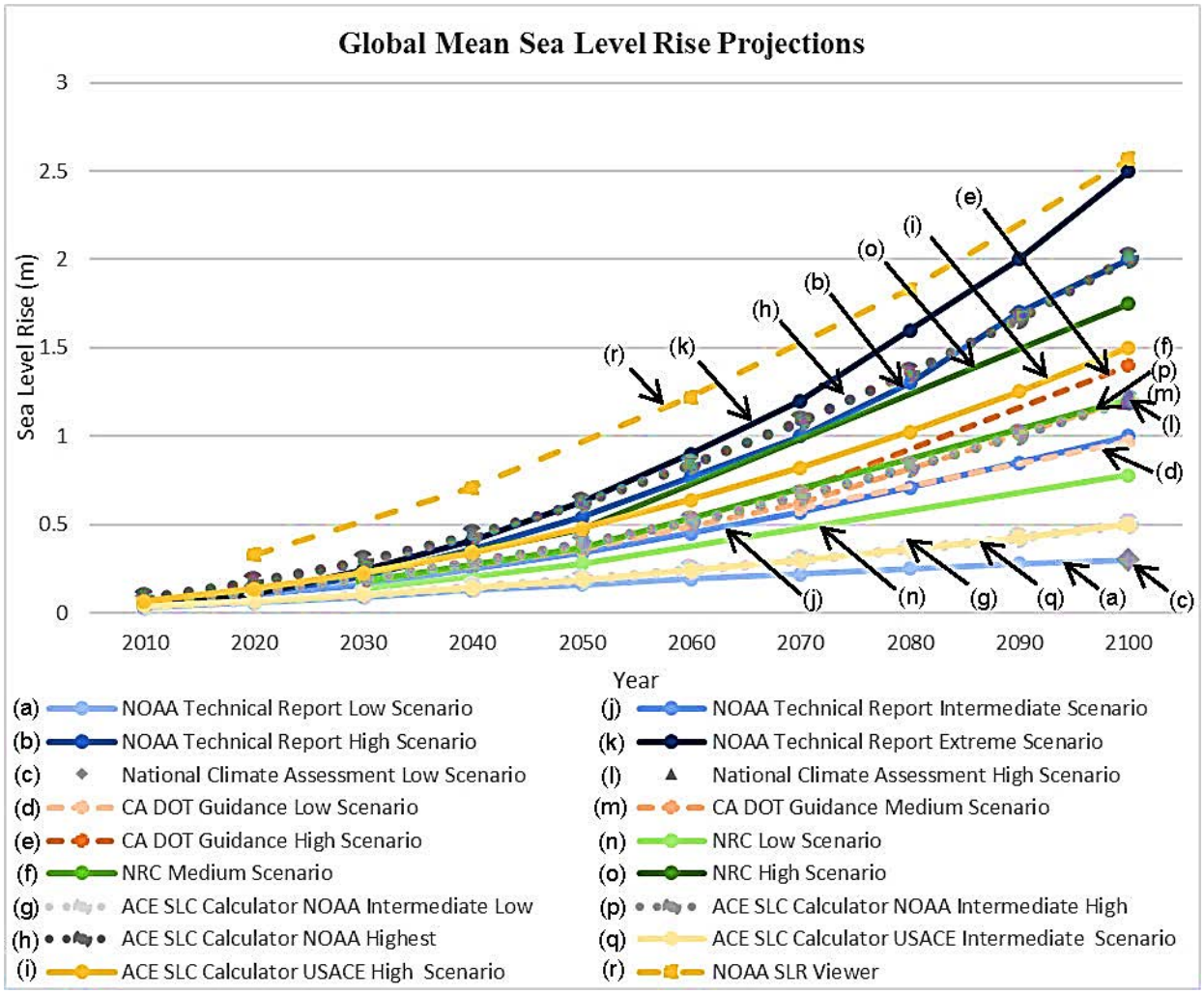

Figure 4-3: Sample of various global mean sea level rise projections through 2100.

Source: FHWA 2017c.

4.3 Climate Modeling

Global Climate Models (GCMs) take GHG data from emissions scenarios and determine what effect they will have on climate variables like temperature, precipitation, and wind. GCMs represent, through physics and mathematics, the highly complex interactions between GHGs, atmospheric warming, oceans, the biosphere, weather patterns, and other natural processes. Figure 4-4 illustrates some of the physical processes covered by GCMs.

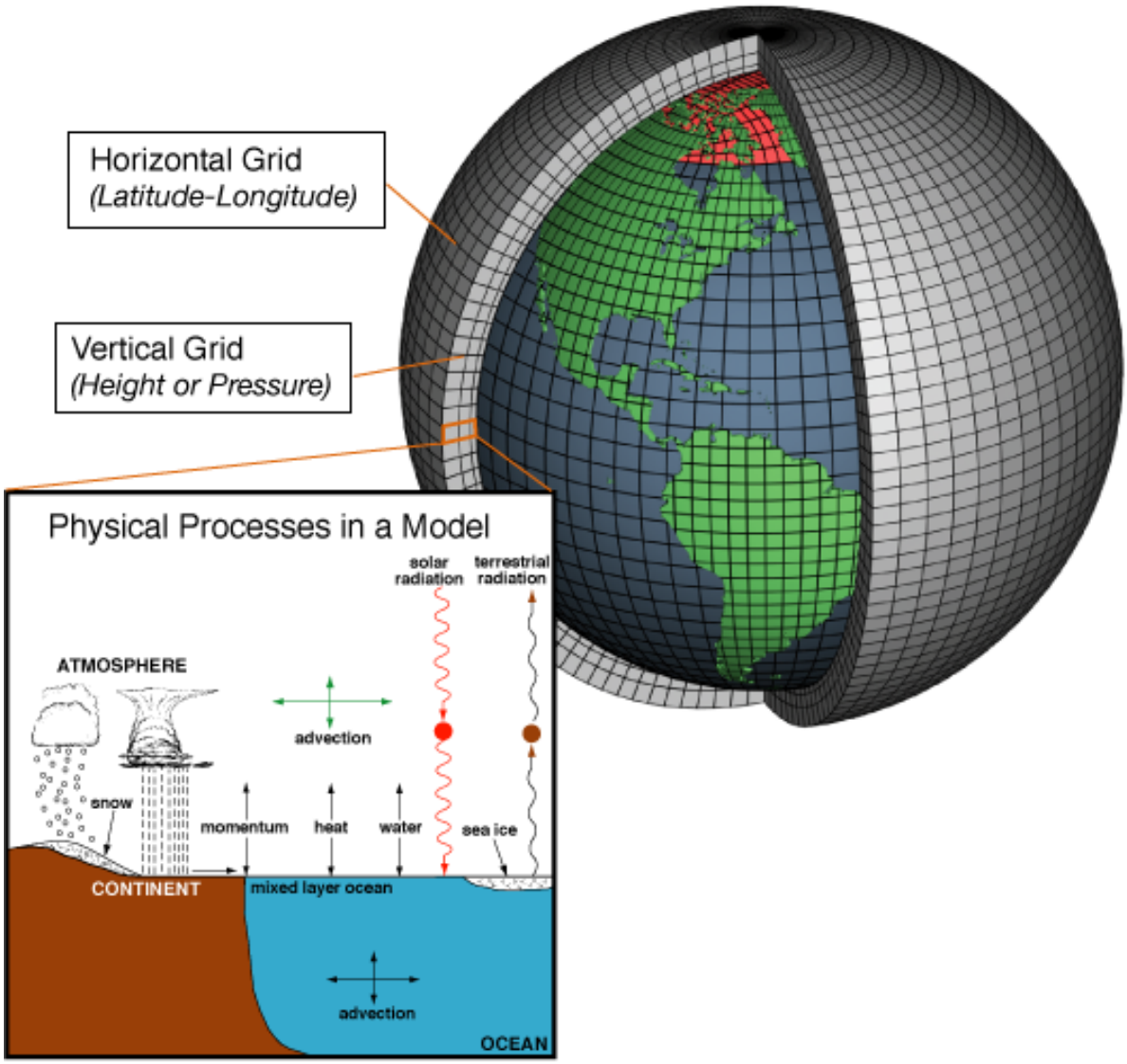

Figure 4-4: Generalized schematic of a Global Climate Model.

Source: NOAA 2017.

As indicated in Figure 4-4, GCMs divide up the world into thousands of grid cells, with each one typically about 50 miles across (the resolution varies depending on the model). Mathematical calculations—conducted by supercomputers—are made individually for each cell considering

the values of neighboring cells. In addition, GCMs have multiple vertical layers to capture different atmospheric and oceanic processes.

Calculations of variables such as temperature, precipitation, and wind are made for each cell at approximately 3-hour intervals and then summarized into daily values for use by practitioners assessing climate change impacts. The calculations are first made by running GCMs with past GHG concentrations. This provides hindcasted results that can be compared to observed climate data and used to calibrate the model. Once the model is calibrated, data on future GHG emissions can be inputted and the model used to project future climate. Most GCMs have been run through at least the year 2100.

Dozens of GCMs have been developed by research institutions around the world. Each GCM is somewhat different in its grid resolution, the equations it uses, and the processes it represents. Therefore, even given the same GHG emissions assumptions from a common RCP, each model will provide a somewhat different projection of future conditions. Determining which GCM's outputs best represent a region of interest can be a challenging exercise. There are few recommendations about which models are the most appropriate to use in most U.S. locations.[5] Practitioners should contact climate scientists familiar with their region for assistance in selecting appropriate models for their area and use.

4.3.1 Downscaling

As noted above, GCM projections of temperature, precipitation, and wind are provided in grid cells that are approximately 50 miles across. Projected values represent an average within each grid cell. Model resolution is primarily determined by computing power; the higher the resolution, the more computing power is needed. GCM resolution has steadily increased as computing power has increased. There can be important climatic differences across 50 miles of land, especially in mountainous and coastal areas.

To address concerns with GCM resolution, downscaling techniques have been developed that increase the resolution of the projections. There are two primary types of downscaling:

- **Statistical downscaling:** Statistical downscaling uses past climate observations to increase the resolution of future climate projections. For example, if one area within a grid cell has historically been 10 percent colder than the rest of the cell (e.g., an area at a higher elevation), then that data could be used to reduce the projected future increase in temperatures for that portion of the grid cell by 10 percent. The drawback of this technique is that it assumes that the relative *differences* in climate conditions between locations will remain the same into the future, which may not always be the case. Among statistical downscaling techniques, use of the Localized Constructed Analogs (LOCA) statistical downscaled datasets is suggested.
- **Dynamic downscaling:** Regional climate models **(**RCMs) can be thought of as small-scale GCMs focused on an individual region. RCMs process GCM output at a finer scale

[5] California is an exception. The State's Department of Water Resources (DWR) went through a process to select 10 models that do a good job at representing the State's climate. Many groups in California are using this guidance to select models for use in vulnerability analyses and for designing individual projects. See CA DWR CCTAG 2015 for more information.

and use many of the same mathematical computations as do GCMs. Unlike statistical downscaling, this downscaling technique can dynamically account for changes in the relative differences in climate between various areas as the planet warms. However, this approach to downscaling is typically more time-consuming and expensive than statistical downscaling, and RCM coverage and scenarios have been limited. Work continues to expand the projections available from RCMs, which may play a growing role in providing climate projections.[6]

Practitioners may wish to contact a climate scientist familiar with their region for assistance in choosing downscaled data that may be appropriate for their area of interest.

4.4 Sources of Climate Projections

Obtaining climate projections that can be useful for system-wide vulnerability analyses or asset-level design applications can be challenging. In the past, raw outputs from climate models often were uploaded to websites targeted to the modeling community. The file formats and accompanying documentation were difficult for practitioners in other disciplines to use. Engineers also had challenges accessing the data, typically putting significant effort to process and translate the data into useful measures for analysis. Recent work has been done to make climate projections more accessible to transportation professionals, including geotechnical engineers.

The FHWA developed the Coupled Model Intercomparison Project (CMIP) Climate Data Processing Tool 2.1 to help transportation professionals obtain and calculate site-specific climate projections for their location of interest.[7] This web-based tool provides statistically downscaled temperature and precipitation projections for the contiguous United States. The tool draws on the Downscaled CMIP5 Climate and Hydrology Projections (DCHP) database.[8] [9] The DCHP database is collaboratively maintained across many Federal agencies.

Other nationwide sources for climate model projections are:

- Coordinated Regional Downscaling Experiment (CORDEX)
- North American Regional Climate Change Assessment Program (NARCCAP)
- U.S. Geological Survey (USGS) Geo Data Portal

[6] https://csengineermag.com/global-climate-modeling/, accessed March 24, 2022.
[7] CMIP is an ongoing effort to coordinate climate modeling work across the various research institutions that have developed climate models. Among other activities, the project ensures consistent inputs are used in the modeling so that results of different models can be compared.
[8] CMIP5 refers to the generations of modeling protocols, with CMIP5 being the most recent protocol for which downscaled projections are available. CMIP5 outputs represent the latest science at the time this report was drafted. CMIP6 projections are under development.
[4] See the *State of California Sea-Level Rise Guidance: 2018 Update* (http://www.opc.ca.gov/webmaster/ftp/pdf/agenda_items/20180314/Item3_Exhibit-A_OPC_SLR_Guidance-rd3.pdf).

State, local, and regional sources may also be available. Practitioners are encouraged to contact climate scientists for suggestions on which datasets might best suit their purposes and how to use the data.

Similar resources are available for sea level rise projections. These include:

- FHWA's Hydraulic Engineering Circular (HEC) 25, *Highways in the Coastal Environment,* which provides a summary of nationally available sea level rise projections
- NOAA's Global and Regional Sea Level Rise Scenarios for the United States (2017 report and 2022 report)
- National Research Council's (NRC) *Sea-Level Rise for the Coasts of California, Oregon, and Washington* report
- U.S. Army Corps of Engineers (USACE) Sea-Level Change Curve Calculator. The calculator is used to obtain local projections of relative sea level rise that account for land subsidence and uplift. Many sources of sea level rise data are available through the tool, including NOAA projections (National Research Council values for the West Coast, projections used by the Department of Defense, and the USACE's own projections)
- U.S. Global Change Research Program's (USGCRP) *Fourth National Climate Assessment, Vol. 1: Climate Science Special Report*

In addition, some States (e.g., California) and regions (e.g., South Florida and Tampa Bay) have formulated their own localized sea level rise projections, often based on scenarios developed by the agencies cited above. Some States and regions also feature planning-level storm surge modeling data that incorporates sea level rise (for example, the USGS CoSMoS modeling effort in California). Whether looking at storm surge with sea level rise or general tidal flooding issues, practitioners should be cognizant of any requirements to use certain sets of projections for analyses, a growing trend among Federal, State, and local governments.

4.5 Uncertainty in Climate Projections

Three general types of uncertainty exist when projecting climate:

- **Scientific (model) uncertainty:** There is incomplete knowledge of how the Earth's climate system will respond to increasing GHG concentrations. Many potential sensitivities are active areas of research in the natural sciences, and consensus has not yet formed on the magnitude of all possible effects. Furthermore, there are different perspectives on how to model the Earth's climate and, hence, multiple GCMs, each with a somewhat different view of how climate will respond to a given amount of GHGs.
- **Scenario (human) uncertainty:** As previously noted, future GHG emissions depend on unknowable factors such as future global population, technology changes, energy use, public policy, etc. This uncertainty is captured by the different RCPs.
- **Natural (internal) variability:** Even absent climate change, weather is variable and natural variations occur regularly.

The uncertainty of climate future may mean using different ways to assess certain geohazards and conduct geotechnical analyses than for other kinds of assessment. The techniques may be

similar, but changes should be made in the way those techniques are employed and which climate inputs to use.

Instead of a single value climate metric, *multiple* input values reflecting the range of plausible future climate scenarios, should be obtained and evaluated within a scenarios-based framework. On projects, different design options should be tested. The following chapters describe how to apply such a scenarios approach with system-wide vulnerability analyses of geohazards (Chapter 5) and with respect to the design of individual facilities (Chapter 6).

5 SYSTEM-WIDE VULNERABILITY ANALYSES FOR GEOHAZARDS

In this chapter, vulnerability refers to the transportation system's degree of exposure to the geohazard, the system's sensitivity to the impacts of the geohazard, and the system's ability to be adapted to reduce susceptibility.

5.1 Identifying Geohazards within an Area

The first step to evaluating geohazard vulnerability is to identify the geohazards that pose a substantial threat to an agency's transportation system. Geohazard threats depend primarily on location parameters, including geography, topography, and geology. In many locations, geologic survey organizations have helped transportation agencies develop geohazard maps. Examples of geohazard identification are presented in the sections below.

5.1.1 Intra-Agency Coordination to Evaluate Considerable Geohazards in California

Geohazards pose a considerable threat throughout much of California, which has experienced some of the most consequential earthquakes and landslides in U.S. history. The California Geological Survey (CGS) serves as a resource for the California agencies responsible for geohazards management, including the State's Department of Transportation (Caltrans), Office of Emergency Services, and Department of Forestry and Fire Protection. Also, many California cities have geologic hazard maps for liquefaction, faulting, landslides, and expansive soils.

CGS has developed and maintains a variety of maps. These include probabilistic seismic hazard maps (see the example probabilistic seismic hazard map in Figure 5-1) and maps for specific seismic regions throughout the State. CGS publishes its resources for assessing seismic hazards along with its maps on its website, https://www.conservation.ca.gov/cgs/geohazards/tsunami/maps

Other CGS maps are of faults throughout the State, historic earthquakes, and recent earthquakes with measured ground motion data, similar to what the U.S. Geologic Survey provides for the entire United States. CGS tsunami inundation maps delineate areas along the State's coastline where a tsunami would be expected to produce flooding. The agency's series of landslide maps generally fall into four categories:

- Landslide-inventory maps, which show historic landslides
- Landslide-hazard maps, which indicate the likelihood of future landslides
- Landslide-risk maps, which indicate the landslide likelihood jointly with landslide consequences
- Landslide-zone maps, which outline areas of high likelihood for landslides

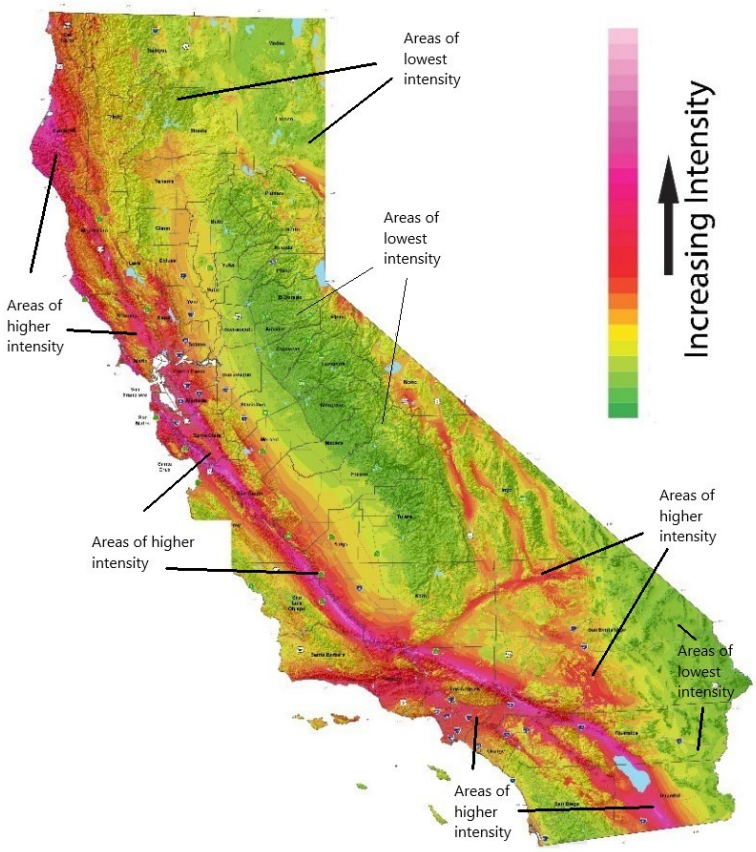

Figure 5-1: Earthquake shaking potential map by the California Geological Society. Map identifies areas of seismic geohazards for the State.

Source: California Geological Society.

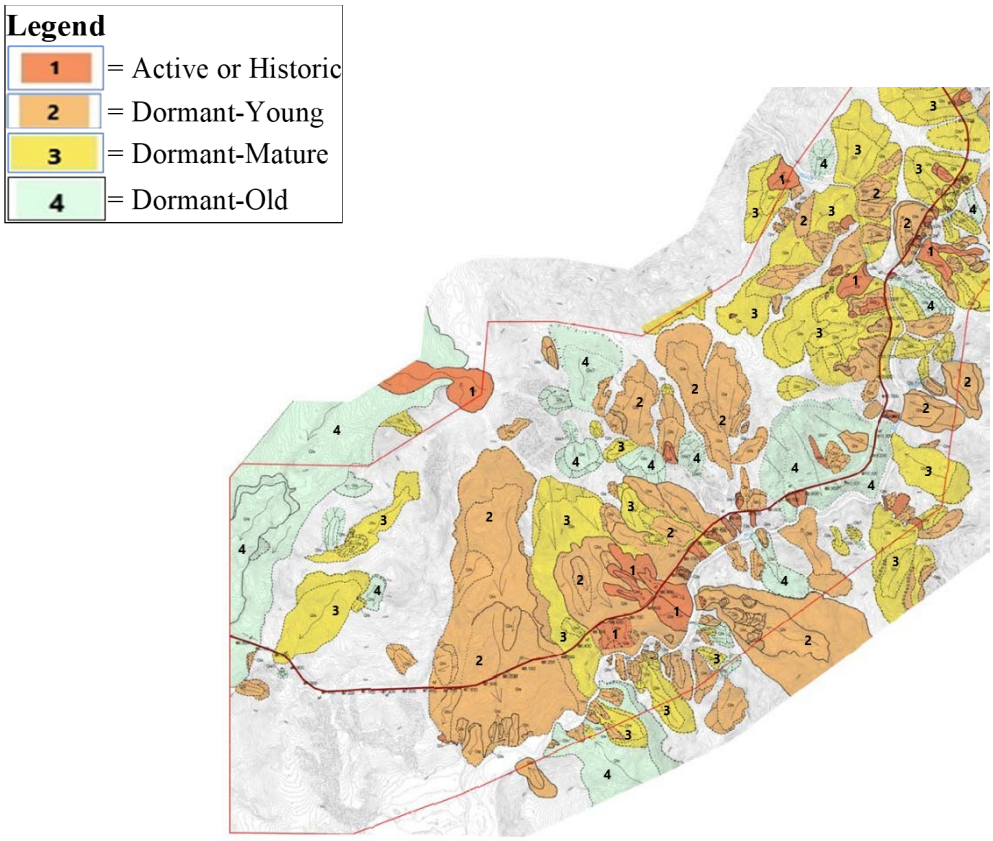

Figure 5-2: Portion of CGS highway corridor landslide map for Highway 299 in Northern California. Five miles of roadway are shown. Colors designate age of historic landslides.

Source: California Geological Society.

CGS coordination with Caltrans began after a 1998 landslide outside Sacramento closed Highway 50 for one month. The landslide resulted in an estimated economic impact of $10 million. In response, CGS developed a series of highway corridor landslide maps for Caltrans. The first set of maps covered a 20-mile stretch of Highway 50 and identified several hundred potential slides. Between 1998 and 2017, CGS produced similar maps for an additional 500 miles of highway. An example is shown in Figure 5-2. The maps are to help Caltrans identify re-routing options and maintain a highway through unstable mountains. Caltrans is working to digitize the maps and implement them through geographic information systems (GIS).

5.1.2 Historical Records to Identify Norway's Geohazards

Norway is a mountainous country with a long, rugged coastline along its western border. The Gulf Stream passes along Norway's coast and results in higher temperatures and greater precipitation than most other locations at such high latitudes. Avalanches, landslides, and floods are the most common geohazards in Norway. Jaedicke et al. (2008) report that landslides and avalanches alone have caused more than 2,000 deaths since the mid-19th century; Figure 5-3 shows deaths due to all geohazards in Norway from 1845 to 1986. Jaedicke et al. explain that landslides and avalanches in Norway include snow avalanches, debris flows, rockfalls, rock avalanches, and landslides involving Scandinavia's infamous quick marine clay deposits. These landslides and avalanches are generally triggered meteorologically, either by extreme precipitation or snowmelt.

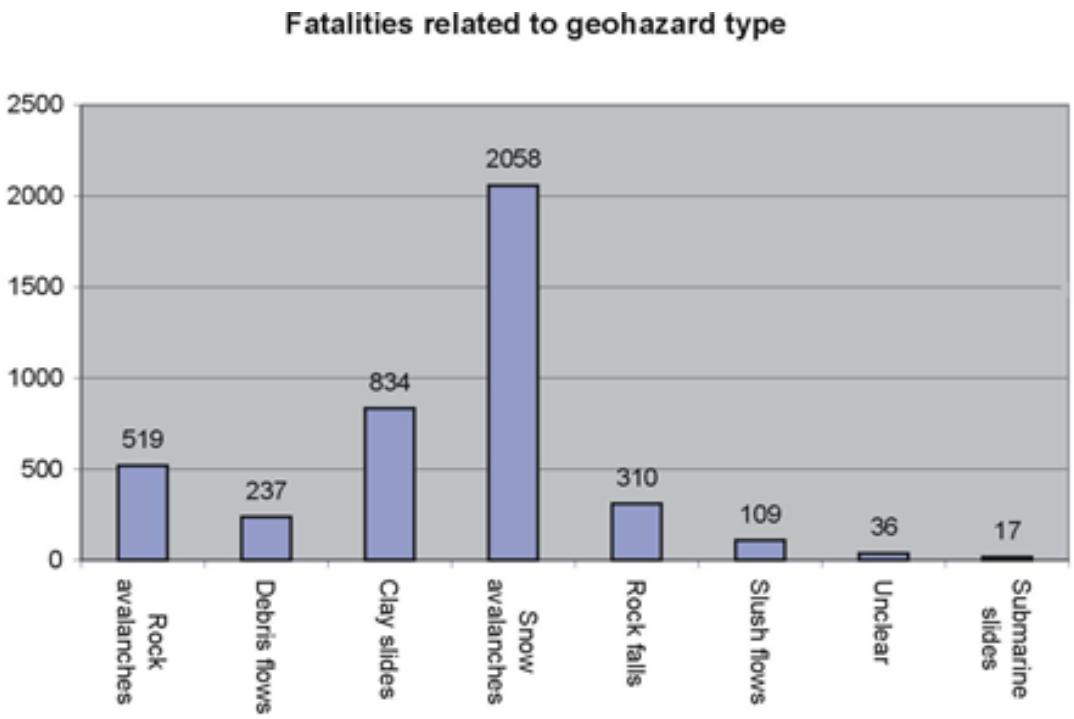

Figure 5-3: Fatalities attributed to geohazards in Norway, 1845-1986.

Source: Jaedicke et al. 2008.

To address the threat of landslides and avalanches, the Norwegian Public Roads Administration (NPRA) teamed with the Norwegian National Rail Administration and the Norwegian Water Resources and Energy Directorate to form a program called NIFS, an abbreviation for natural hazards, infrastructure, floods and landslides/avalanches. The program developed several work packages that include:

- Natural hazards strategy
- Preparedness and crisis management
- Land use, data coordination, and analyses of risk and vulnerability
- Monitoring and forecasting landslide risk
- Flood and floodwater management
- Quick clay (due to the risk of rapid landslides)
- Landslide/avalanche and flood protection measures

In 2016, NIFS published a final report documenting its efforts (Aunaas et al. 2016). NPRA and the Norwegian Water Resources and Energy Directorate also collaborated with the Norwegian Meteorological Institute and the Norwegian Mapping Authority to develop a website, www.xgeo.no, that allows users to view historical landslides and snow avalanches on a map of the country. A screenshot is shown in Figure 5-4. The map displays all documented landslides for the 365 days preceding September 22, 2017. Users can select the range of dates for events, zoom in to focus on specific portions of the country, and view event records, which often include

photographs. In addition, the website maps meteorological data for a wide variety of records, including precipitation, groundwater level, and temperature. The website also includes future projections for the meteorological datasets.

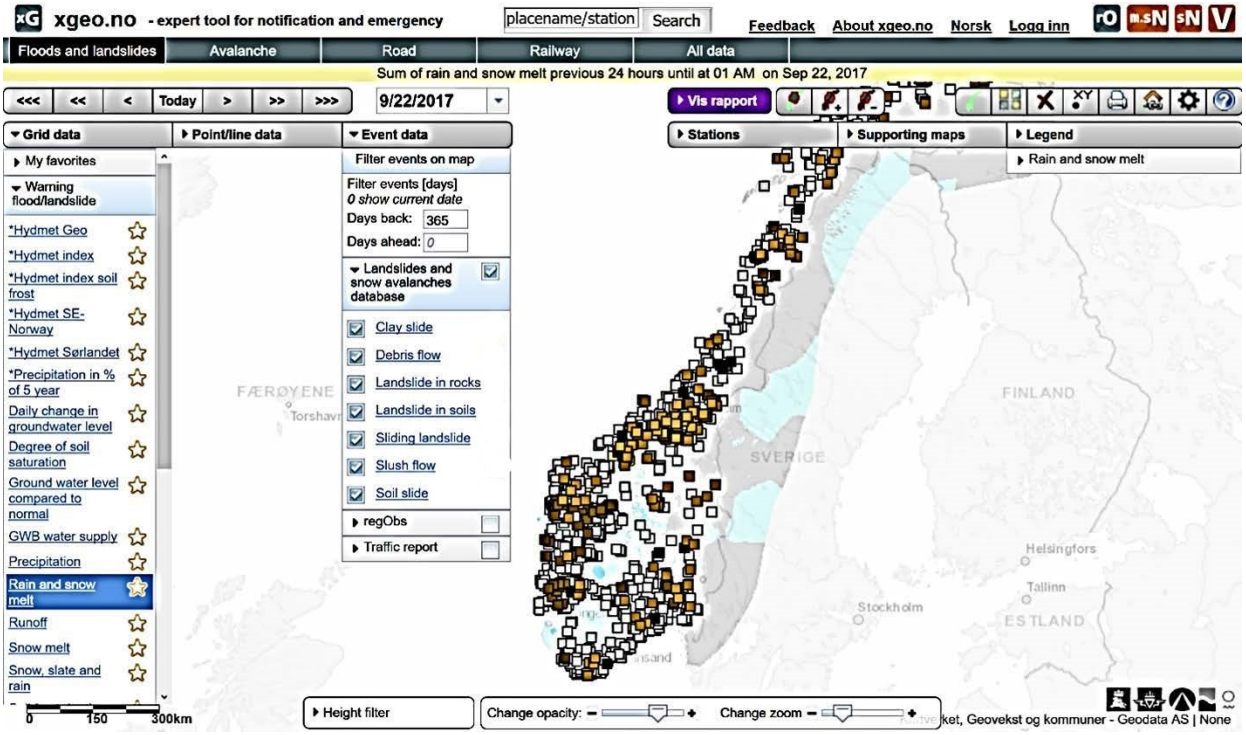

Figure 5-4: Screenshot from www.xgeo.no showing all documented landslides and snow avalanches in Norway for the year preceding September 22, 2017.

5.1.3 Oregon DOT: Engage and Train Maintenance Crews

Like California and Washington, Oregon is threatened by many geohazards, including coastal erosion, earthquakes, flooding, landslides and rockslides, debris flow, tsunamis, and volcanoes. The State's recent history with geohazards is dominated by flooding and landslides, mostly in response to extreme precipitation events. In December 2007, a major storm hit northwestern Oregon and Washington. The storm was notable for its hurricane force winds, with recorded wind speeds of 129 miles per hour on the coast. The storm was blamed for at least 18 deaths. The storm's consequences on infrastructure systems and emergency response efforts were documented in a monograph for the American Society of Civil Engineers (ASCE) Lifeline Series (Elliott and Tang 2012). The monograph estimated total direct losses at $300 million, with $62 million in infrastructure damage; indirect losses were estimated to be at least $1.5 billion. Flooding from the storm closed all highways between the Willamette Valley and the northern Oregon coast for the second day of the storm. Subsequent debris flows and landslides led to other closures.

Oregon DOT (ODOT) relies on agency maintenance personnel to identify potential landslides and rockfalls. In ODOT Region 1, which includes Portland, geotechnical engineers and geologists rotate through on-call weeks to field calls 24/7 from maintenance crews about potential issues. Each year, technical staff hold training sessions to provide maintenance

personnel information about when to contact on-call staff, and to remove any reluctance maintenance personnel may have about making contact. The engineers instruct the maintenance crews to call if they spot about 1 cubic yard of slide debris and tell maintenance crews to call and leave the area if they spot 5 or more cubic yards of debris.

5.2 Assessing Vulnerability of Transportation System to Geohazards

After identifying the general geohazards that create vulnerabilities within the State, the next step is to evaluate vulnerabilities associated with each geohazard and how they may impact transportation assets. Assessing geohazard vulnerability is typically considered within a risk-based framework, where risk is the product of the probability and the consequences of failure. In the case of geohazards, "failure" can be considered the event that a geohazard occurs and produces some level of consequences on the transportation system. Calculating geohazard risks is generally difficult because of considerable uncertainties associated with the likelihood and consequences of geohazards. However, geohazard management systems that are risk-based will likely produce better decisions than systems that do not formally consider risks, even if estimates of risk are associated with a large uncertainty.

Estimates of risks should include the probability of a geohazard failure occurring, the frequency or rate of such a failure, and the consequences of the geohazard. The probability of geohazard failure can be estimated from expert opinion, historical records, or from both, along with consideration of the effects of future climate changes. The expert opinion method involves estimating geohazard failure rates drawing on professionals' judgment, preferably professionals with experience in the specific geohazard and geographic region. The historical records method involves calculating frequencies based on known geohazards occurrences with time.

For example, if a highway corridor has documented rockslides during 5 of the previous 20 years, then the annual probability of a rockslide could be estimated as approximately 1 in 4, or 0.25. For some geohazards, the probability of failure estimate may be more reliable if it is calculated considering both the probability of the geohazard event occurring (e.g., the probability of a rockfall) and the probability of the event impacting the transportation system (e.g., the probability of the fallen rock striking the roadway). For other types of geohazards, consideration of the conditional probabilities is unnecessary, for example, the potential for a massive landslide that would invariably close a highway corridor.

Consequences of geohazards can include many impacts: fatalities, injuries, direct costs associated with repairing or replacing transportation assets, and indirect costs to the regional economy associated with downtime, among others. One common approach is to consider each consequence in terms of dollars. To estimate the costs of consequences, any number or combination of methods can be used. One approach is to assign a "ballpark estimate" cost figure. More reliable estimates can be achieved by using historical agency records to develop unit costs for similar events. To facilitate future use of historical agency costs, agencies can track expenses associated with geohazard events using unique accounting codes. More reliable cost estimates can also be achieved using conventional cost-estimation techniques, such as those that would be used for other agency construction projects, or by soliciting bids for a proposed geohazard mitigation project. Combinations of these cost-estimating techniques can be used as well. It may

also be possible to utilize FEMA's Hazus tool, perhaps with some modification. Typically, the geohazards consequence assessment should also include socioeconomic factors. Chapter 9 presents an analysis of socioeconomic factors.

Examples of geohazard vulnerability assessments are provided below. Based on the peer exchange and literature review, transportation agencies that have assessed geohazard vulnerabilities have frequently done so with some degree of empiricism, using qualitative measures as surrogates for the quantitative approach. As with identification of geohazards, many transportation agencies report benefits from working with other State agencies or scientific organizations to assess geohazard vulnerability.

5.2.1 FHWA Unstable Slope Management Program for Federal Land Management Agencies

Federal Lands transportation corridors for roads and trails contain unstable slopes, both natural and constructed (cut slopes and embankments). These slopes are all subject to some form of failure from slow creep failures to sudden rockfall. The slope failures may be simple maintenance issues, but sometimes they are serious incidents that cause loss of life, injury, and property damage; block use of roads or trails; and cost millions of dollars to repair. Federal engineering geology and geotechnical staff recognize that geotechnical asset management (GAM) could be adapted to Federal Land Management Agencies (FLMAs) and State DOTs. So, Federal partners of Federal Lands Highway Divisions requested development and deployment of a tool to help locate, assess, and manage linear transportation (roads and trails) slope assets.

The primary objective was to develop an unstable slope management program (USMP) based on transportation asset management (TAM). The USMP would help multiple FLMAs, including agency transportation departments with lower traffic volumes, manage their unstable rock and soil slopes, often referred to as slope assets. TAM uses economic and engineering analyses to create a process for maintaining, preserving, rehabilitating, and replacing assets. The process is to maintain assets in good repair over their lifecycle and for the minimum practical cost. The USMP was also founded on performance management and risk management principles.

During the project, these items were developed: a standardized rating tool, maintenance tracking and new slope failure event forms, a database with searching and reporting capabilities, and a GIS-based map to display unstable slopes and rockfalls along transportation corridors. Examples of performance metrics for geotechnical assets were established. Also developed were an assortment of scalable and flexible benefit/cost analysis procedures for differing levels of available information for prioritizing slope work. A quantitative risk analysis procedure was developed to support further risk assessment for some transportation agencies. In addition, mobile software applications were developed for users to conduct rapid field inventory and inspection work.

By 2019, the USMP had approximately 3,000 slopes entered into the system, primarily by the National Park Service, Forest Service, local transportation agencies (Counties), and some State DOTs. For information about the project and tools developed, visit https://highways.dot.gov/federal-lands/geotechnical.

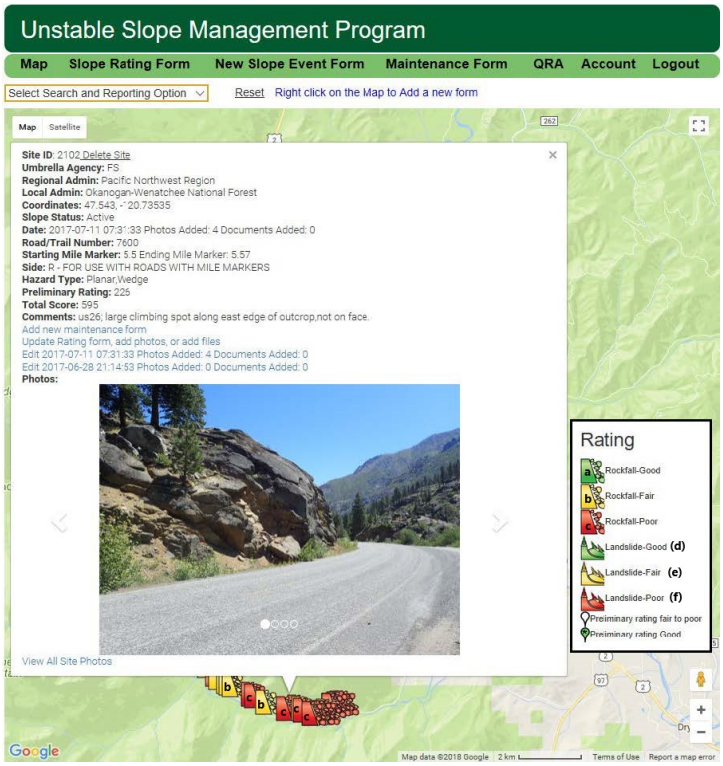

Figure 5-5: Screenshot from the Federal Land Management Agencies website.

5.2.2 FEMA Hazus Tool

Hazus is a software tool that FEMA developed to maintain models for estimating potential losses from earthquakes, flooding, hurricane winds, and tsunamis.

For a given area and type of *risk* (e.g., 100-year flood), the Hazus model determines the risk exposure, predicts the event intensity (e.g., depth of flooding), and estimates various types of losses based on the analysis area's assets (e.g., direct and indirect economic losses). The model is built from several databases, and users have the option of augmenting or replacing the default databases with local information. The Hazus tool and user resources are available to view and download from FEMA.gov, https://www.fema.gov/flood-maps/products-tools/hazus.

FEMA provides three levels of analysis through the Hazus software:

- Level 1 produces simple estimates that participants in FEMA's Basic Hazus training course can perform.
- Level 2 improves on Level 1 estimates by including local data about hazard information and/or asset inventories.
- Level 3, the most advanced analysis, includes detailed, expert information to improve estimates about losses, such as structural impacts and damage to water systems. FEMA recommends the Level 3 analysis for those with expertise.

Hazus can perform similar analyses for risks associated with earthquakes, hurricane winds, tsunamis, and combinations of these hazards. Hazus inventories include “lifeline” transportation and utility structures, but FEMA notes that predicting damage to lifeline networks is complicated. Hazus does not have capabilities for modeling roadway infrastructure losses or landslide risks.

FEMA indicates that Hazus models are highly sensitive to hazard input. Accordingly, FEMA recommends enhancing the Hazus inventory with user-supplied data. Soils maps can greatly improve estimates of earthquake loss estimates. Validation studies are also valuable resources.

5.2.3 Tools for Evaluating Seismic Vulnerability in California

The California Geological Survey (CGS) manages the California Strong Motion Instrumentation Program (CSMIP) in addition to developing maps, as described in the previous section. CSMIP measures shaking of the ground and structures, and reports data immediately after seismic events. The program was established after the 1971 earthquake. Initially, data collection was performed over weeks to months, and information was primarily used to improve design and building codes. As remote data collection methods were introduced, CSMIP data delivery time decreased. Currently, CSMIP information is available online within 10 minutes of an event. Use of CSMIP information has evolved to include emergency response efforts by the California Office of Emergency Services.

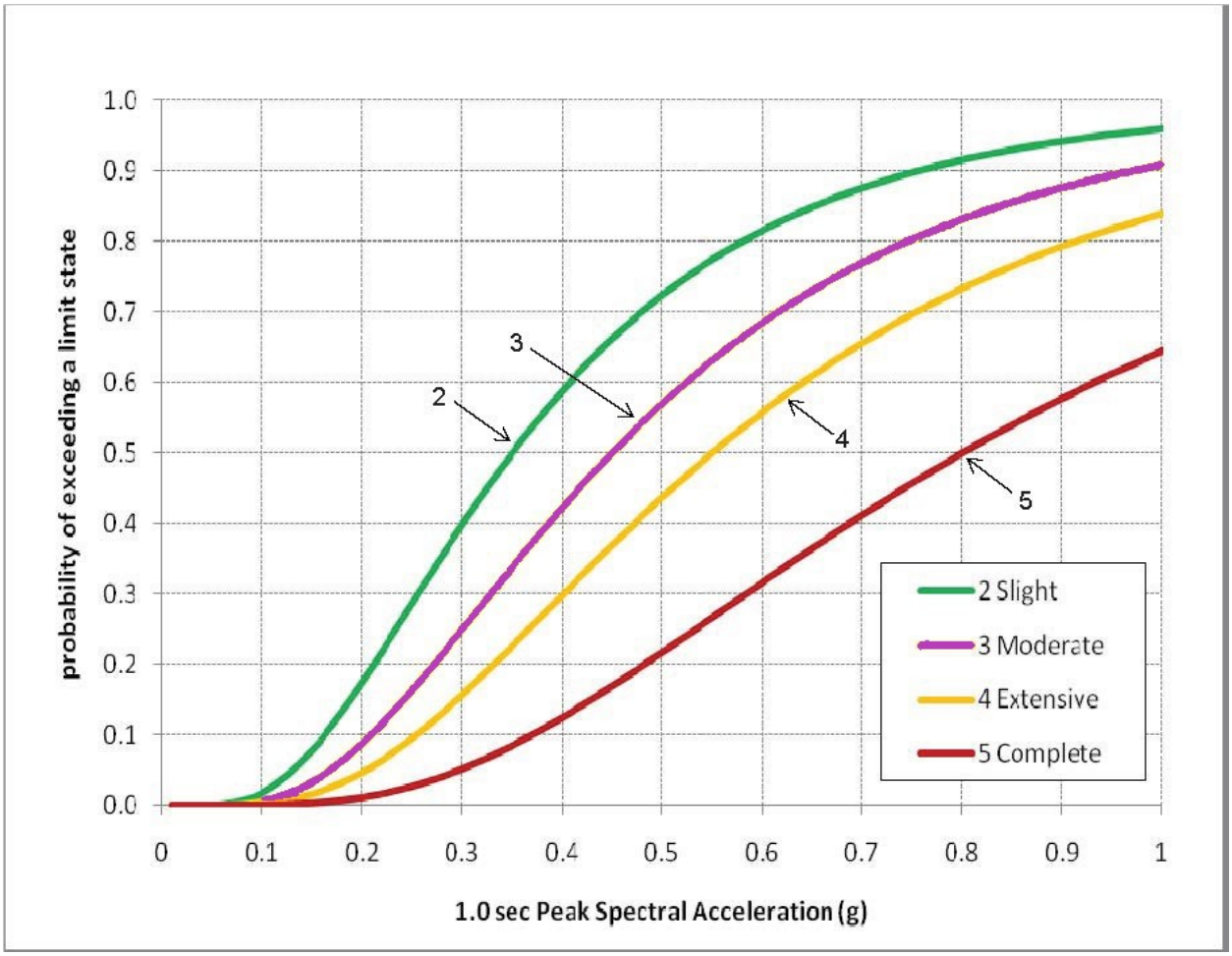

Figure 5-6: Example of seismic bridge vulnerability information for Caltrans.

Source: Turner 2016.

CSMIP information includes ShakeMaps that show contours of ground accelerations for the area impacted by an earthquake. ShakeMap is a product of USGS working with regional seismic networks, including CGS. ShakeMaps are available online within 10 minutes of a seismic event. Caltrans uses CSMIP information to prioritize emergency response activities after a seismic event. Another USGS product, ShakeCast, compares ShakeMap information to vulnerability

information specific to each bridge in the impacted area. An example is shown in Figure 5-6; the plot shows predicted probabilities of various degrees of damage (from slight to complete) for different levels of ground motion. The vulnerability information is based on seismic analysis of each Caltrans bridge. Caltrans uses ShakeCast to compare the CSMIP ground motions to the database of vulnerability records to develop a prioritized list of bridge inspections. That list is automatically emailed to relevant Caltrans personnel after a seismic event. Caltrans has considered developing a tool similar to ShakeCast, but for landslide hazards.

In addition to managing CSMIP, CGS provides earthquake loss estimates for California. The estimates are frequently updated to reflect changes in population and development, as well as improvements in models for predicting shaking levels. The estimates are based on Hazus models, but with local and regional information, including soil data and response models. The most recent loss estimates by CGS are shown in Figure 5-7 (Chen et al. 2016). The total annualized earthquake losses for California were estimated to be $3.7 billion; this figure is generally associated with building damage and does not include most of the indirect economic losses or damage to infrastructure.

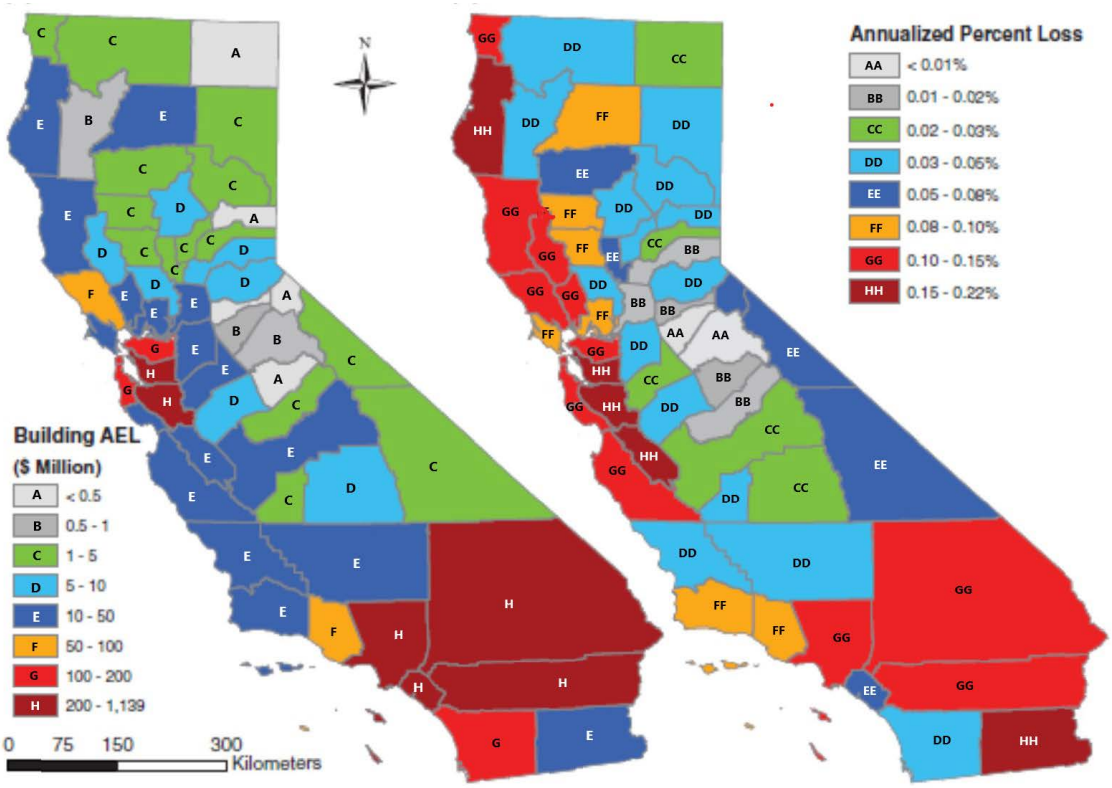

Figure 5-7: Annualized Earthquake Loss and annualized percent loss from CGS hazard analysis.

Source: Chen et al. 2016.

5.2.4 REDARS 2

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) at the University of Buffalo developed a methodology for seismic risk analysis of highways, REDARS 2 (Risks from Earthquake Damage to Roadway Systems). As documented by Werner et al. (2006), the methodology was programmed into a software package with an example application to the Los Angeles highway system. The software package is technologically outdated, but the methodology has useful characteristics. The methodology is similar to FEMA's Hazus tool: It is risk-based and considers physical, economic, and social consequences. But REDARS 2 is specific to highway systems; it includes models for considering traffic congestion and the impacts of downtime.

5.2.5 Rating Systems to Empirically Assess Vulnerability to Landslides and Rockslides

Oregon DOT (ODOT) was an early pioneer of addressing rockfall hazards, leading the pooled fund study that culminated with the 1989 *Rockfall Hazard Rating System* (RHRS) (Pierson et al. 1989). ODOT's system involved inventorying rock slopes and categorizing them as A, B, C, D, or E based on rockfall potential and expected consequences. ODOT's rock slopes still have RHRS ratings, but the agency has since developed the Unstable Slopes Program to address hazards due to landslides and rockslides. The Unstable Slopes Program is less complicated than RHRS and may be easier to implement by non-technical on-site personnel (Pierson et al. 1989). The Unstable Slopes Program assigns scores as the product of a hazard score, a maintenance benefit-cost factor, and a highway classification factor. Descriptions of each component are presented in the tables shown in Figure 5-8 (Mohney 2009). The hazard score is based on qualitative factors. The most significant factor, failure hazard, accounts for the probability of landslide or rockslide, as does the maintenance frequency. The other factors account for consequences. Roadway impact encompasses both economic consequences, as well as mobility and safety impacts. Traffic volume combined with highway classifications generally account for mobility impacts. Crashes and traffic account for safety impacts. Scores from the rating system are included in ODOT's Statewide Transportation Improvement Plan (STIP), where they are used to prioritize mitigation projects.

Hazard Score

Failure Hazard	Very small or insignificant failures that do not affect the roadway (Not Scored)	**Low Hazard:** Slower slides with low potential for causing a road hazard (9 Points)	**Medium Hazard:** Slides that have not moved suddenly in the past but have the potential to cause a road hazard (27 Points)	**High Hazard:** Rapid slides that have created road hazards in the past; and all debris flows and rockfalls (81-100 Points based on sight distance)

Roadway Impact	**Landslide:**	Would only affect shoulder during major failure (3 Points)	Two-way traffic would remain after a major failure (9 Points)	One-way traffic would remain after a major failure (27 Points)	Total closure in the event of a major failure with 0-3 mile detour (54 Points)	Total closure in the event of a major failure with 3-10 mile detour (70 Points)	Total closure in the event of a major failure with 10-60 mile detour (85 Points)	Total closure in the event of a major failure with >60 mile detour (100 Points)
	Rockfall:	Rocks are completely contained in the ditch (3 Points)	Rocks fall onto the shoulder (9 Points)	Rocks enter the roadway (27 Points)	No ditch; all rocks enter the roadway (81 Points)	Rocks occasionally fill all or part of a lane (100 Points)		

Annual Maintenance Frequency	Once every 5 years or less (0 Points)	Once every 4 years (13 Points)	Once every 3 years (17 Points)	Once every 2 years (25 Points)	Once every 1 to 2 years (38 Points)	Once a year (50 Points)	1 to 2 times a year (56 Points)
	2 times a year (63 Points)	2 to 3 times a year (69 Points)	3 times a year (75 Points)	3 to 4 times a year (81 Points)	4 times a year (88 Points)	4 to 5 times a year (94 Points)	5 times a year or more (100 Points)

Average Daily Traffic	0-499 (11 Points)	500-999 (22 Points)	1,000-2,999 (33 Points)	3,000-5,999 (44 Points)	6,000-11,999 (56 Points)	12,000-23,999 (67 Points)	24,000-47,999 (78 Points)	48,000-95,999 (89 Points)	96,000 and over (100 Points)

Accident History	No accidents (3 Points)	Vehicle or property damage (9 Points)	Injury (27 Points)	Fatality (100 Points)

Maintenance Benefit-Cost Factor

20-Yr Maintenance Cost / Repair Cost	Factor
> 0.0 - 0.2	0.5
≥ 0.2 - 0.4	0.75
≥ 0.4 - 0.6	1
≥ 0.6 - 0.8	1.06
≥ 0.8 - 1.0	1.12
≥ 1.0 - 1.2	1.18
≥ 1.2 - 1.4	1.24
≥ 1.4 - 1.6	1.3
≥ 1.6 - 1.8	1.36
≥ 1.8 - 2.0	1.42
≥ 2.0	1.5

Highway Classification Factor

District 1	Regional 1.05	Statewide 1.1	Interstate 1.2

Figure 5-8: Tables for assessing landslide and rockfall hazard risk scores for ODOT.

Source: Mohney 2009.

5.2.6 Rating Systems by Other State Agencies

North Carolina DOT (NCDOT) has estimated that it responds to major slide events in the mountainous western half of the State approximately once every two weeks during the rainy seasons. In 2009, a rockslide along I–40 just south of the Tennessee border led to a 6-month closure of the interstate and $10 million in costs to clean up. The official detour was more than 100 miles long. HDR Decision Economics (2010) estimated the transportation costs associated with the detour to be $175 million, which does not account for impacts to the local and regional economies.

In 2014, NCDOT began developing a system for management of hazards associated with rockfalls, rockslides, landslides, and embankment failures. The agency's program was based on a rating system in which individual slopes are evaluated by NCDOT engineers or geologists. Information on the slopes, including a breakdown of the rating, photographs, and any historical documents, is stored in the agency's GIS system. The GIS system could be accessed by the public via an ArcGIS website set up by NCDOT. NCDOT's rating system was based on 12 factors (several with sub-factors) that are listed below. The first eight factors addressed consequences, including economic, mobility, and safety impacts. The remaining four factors primarily addressed the probability of failure.

Factors in NCDOT's rating system:

1. **Route type** has six levels ranging from interstate to tertiary route. The route type is the most significant factor in the agency's rating system.
2. **Detour factor** accounts for the length and type of detour that would be needed.
3. **Failure type and volume**, where type differentiates among rockfalls, rockslides, landslides and embankment slides, reflecting the general hazards associated with each. For example, North Carolina landslides are typically slow moving and therefore less hazardous than a rockfall, which is typically instantaneous. Failure volume indicates the significance of repair expenses.
4. **Average vehicle risk** is based on Budetta (2004) that represents the spatial probability of a vehicle being in the failure zone at the time of failure. The factor is calculated from average daily traffic, anticipated length of slope failure impacting the roadway, and speed limit.
5. **Roadway impedance** accounts for the proportion of roadway blocked by width.
6. **Pavement damage** accounts for potential maintenance costs. This factor has a relatively limited impact on the overall rating.
7. **Secondary roadway impact** accounts for the time necessary to complete repairs. The agency has not developed a strict definition for this factor yet; it is not fully implemented in the rating system.
8. **Failure incidence** accounts for previous failures of the subject slope.
9. **Precipitation amount** accounts for the sensitivity of the subject slope to rainfall events. Johnson and Kuhne (2016) note that most landslides and embankment slides in North Carolina occur in response to rainfall.
10. **Maintenance frequency** reflects how regularly the slope has been maintained in its recent history.
11. **Groundwater** accounts for any visible groundwater seeping from the subject slope.
12. **Previous remediation** accounts for previous mitigation work, which reduces the risk.

Johnson and Kuhne (2016) present additional details of the rating system. They also provide five example ratings, which are summarized in Table 5-1.

Table 5-1: Summary of Example NCDOT Slide Ratings, from Johnson and Kuhne (2016)

Location	Description	Photograph	Rating
I–40, Mile Marker 7	• High traffic, interstate site • Site has history of rockfalls, some of major significance (HDR, 2010) • Complete design and reconstruction project in 2016		Before: 1,814 After: 103
I–40, Mile Marker 53	• High traffic, interstate site • 200-feet high • Raveling slide with continuous groundwater seepage • No maintenance incidents, failures, or repairs in 50 years		179
U.S. 19, Maggie Valley	• Slow-moving landslide with high volume • Annual maintenance activities remove approximately 50 cy of material from roadway shoulder, which coincides with the toe of the slope. • Low score reflects the agency's ability to deal with slide via maintenance activities without impacting roadway		381

Location	Description	Photograph	Rating
U.S. 276, Waynesville	• Slow-moving embankment slide • Annual maintenance for pavement slump led to accumulation of 10 feet of additional asphalt • Slide was recently repaired by flattening slope and realigning the roadway • Two-lane road with short detour		Before: 873 After: 134
U.S. 64, Macon County	• Major route with potential slide causing significant detour • Major landslide in 1989 was heavily mitigated, but reactivated in 2013 due to record rainfall • Soil over weathered rock • Adjacent to roadway		793

5.2.7 Oregon: "Lifeline" Routes and Statewide Effort to Achieve Seismic Resilience

ODOT has been actively working toward earthquake resilience. In 2013, Oregon's seismic safety commission published *The Oregon Resilience Plan*. The main conclusion from the report was that the State's infrastructure was "poorly prepared" for the threat of a Cascadia earthquake, and significant action was needed to begin building resilience. In 2016, the Governor of Oregon appointed the State's first resiliency officer, who was charged with coordinating among State agencies to develop a coherent resiliency plan.

The State's *Resilience Plan* recommended seismically retrofitting all "lifeline" routes in and out of major business centers by 2030. Lifelines are described by USGS as "structures that are important or critical for a community to function." Lifelines can include roadways as well as other infrastructure components, such as sewers, power lines, communications lines, and others. ODOT identified three tiers of lifeline routes in the *Resilience Plan* (Oregon Seismic Safety Policy Advisory Commission 2013):

- **Tier 1** routes comprise a small "backbone" system of the most critical routes. Tier 1 routes provide access to vulnerable regions, major population centers, and vital rescue and recovery operations.
- **Tier 2** is a larger network that reaches most urban areas and major commercial centers.
- **Tier 3** is a more complete network.

These tiers have been the prioritization basis for the agency's efforts to meet the goal of seismic resilience by 2030.

5.2.8 Norway: Addressing Vulnerability in Planning, Design, and Operations Phases

In response to the challenges of geohazards and climate change adaptation, the Norwegian Public Roads Administration (NPRA) implemented tools for planning and design, operations and maintenance, and emergency preparedness. Many of the tools were developed in collaboration with academic institutions and other government agencies.

NPRA adopted Norway's NIFS (natural hazards, infrastructure, floods, and slides) program's recommendation to incorporate vulnerability analyses in the planning phases of projects. According to NPRA's principal engineer tasked with coordinating climate change adaptation activities, the project planning phase is often the best opportunity to reduce geohazard risks. NPRA emphasized the use of hazard maps and site visits to identify potential events in advance. An example of hazard maps was presented in Section 5.1.2; the xGeo website, www.xgeo.no, can be used to gather data about historical geohazard events.

Efforts to reduce geohazard risks and improve climate change resilience were also incorporated into NPRA design guidance. For instance, in 2011, the agency updated its hydraulic design guidance to move from a 100-year to a 200-year return period for floods. The agency also implemented an additional safety factor on calculated hydraulic capacities that accounts for uncertainty in the analyses, including uncertainty due to climate change.

Geohazards were also considered. The agency implemented a risk management system for landslides. For example, a December 2015 survey reported protection needs for 1,700 potential landslides, of which 300 were considered high priority. NPRA aimed to mitigate risks for the high-priority sites within 20 years. NPRA also worked to improve the information it provided to its roadway contractors (who operate and maintain stretches of roadway) to include emergency plans and detailed histories of geohazards and repairs for the contracted stretch of roadway.

5.3 Communicating Geohazards Risk to the Public and Decision Makers

Effective public communication is critical to ensuring transportation system users understand geohazard risks. Those users are more likely to prepare for and respond to geohazard events, and to support the sometimes costly measures that may effectively mitigate geohazard risks. Communication of geohazard risks to the public should generally focus on socioeconomic risks, the topic of Chapter 9.

Federal-aid recipients are responsible for involving the public, including traditionally underserved and underrepresented populations in transportation planning and complying with participation and consultation requirements in 23 CFR 450.210 and 23 CFR 450.316, as applicable. "Underserved populations" include minority and low-income populations but may also include many other demographic categories that face challenges engaging with the transportation process and receiving equitable benefits (FHWA 2015).

In alignment with the President's Justice40 Initiative Guidance, the USDOT's Equity Action Plan, and FHWA's Environmental Justice Reference Guide, FHWA expects Federal-aid recipients to engage with all impacted communities and community leaders, including underserved populations, and to ensure they have opportunities for meaningful and

representative public participation engagements (OMB 2021, USDOT 2022, FHWA 2015). Federal-aid recipients should work to gain insight on the unique circumstances impacting various disadvantaged and underrepresented groups so that new and effective channels for communication may be developed. Additionally, Federal-aid recipients should use this information to inform decisions across all aspects of project delivery including planning, project selection, and the design process. While not all geohazard projects are funded through the Federal-aid Highway Program, FHWA encourages this approach as a communications best practice for transportation projects. In addition, Federal-aid highway projects can support the Justice40 Initiative, which establishes a goal that at least 40 percent of the benefits of federal investments in climate and clean energy infrastructure are distributed to disadvantaged communities. (OMB 2021).

Mileti et al. (2004) describe two distinct forms of public communications about hazards: education and warning. Education communications seek to inform the public about risks far in advance of any specific event. Most transportation agencies routinely engage in education communications related to safety goals, such as campaigns to promote seatbelt use and discourage texting and driving or impaired driving. Public warning communications are specific to a unique hazard event and occur in the days or weeks just prior to and during the event.

Most users are at least minimally familiar with most geohazards. Communications focusing on what the geohazard is and why a region is particularly susceptible typically provide a sufficient introduction.

Technical concepts that may be used for public communications relate to identifying the risk, its likelihood, and potential consequences. Mileti et al. (2014) contend that communication of likelihood estimates should generally be limited to engineers and scientists, and not emphasized to the public, as people tend to consider future events as something that either will or will not happen. Public communications about likelihood, however, can be framed in terms of return periods. For instance, "A major earthquake is expected to impact the Portland area within the next 50 years, and the chances are just as great tomorrow as they are 50 years from tomorrow." Consequences typically are most readily understood in dollar terms, though can also be explained effectively in terms of lives lost or injuries sustained.

In many cases, communication of non-technical information is as important as communicating technical concepts. Non-technical information includes suggested procedures for geohazard preparedness and emergency response information for active events. In both situations, developing simple and clear instructions is critical. It is also important to develop broad communication strategies that span the range of communication channels to reach as much of the public as possible. In addition to clarity and a broad stream of communications, Mileti et al. explain several other "laws" of public hazard communications. These include:

- Communicate information through both technical and non-technical sources, and preferably using sources familiar to the public.
- Repeat information and present it consistently.
- Use appealing graphic design to convey communications.
- Emphasize steps that members of the public should take to prepare themselves.

- Provide means for finding additional information.

Table 5-2 lists some of the available communication methods. Risks should be part of all dialogue. There are costs of inaction that should be captured and applied to decision-making.

Other means of communication may be more appropriate when communicating geohazards risks to technical professionals. One example is risk registers, which typically involve a plot of consequences versus likelihoods for various potential events alongside a table with potential mitigation strategies. Risk registers are commonly used in the tunneling industry. Another example is the "risk cube," a concept that has been used in geotechnical asset management and is discussed in detail in Chapter 7.

Table 5-2: Methods for Communicating Geohazard Risks to the Public

Communication Method	Comments
Emergency Alert System	National system exists for most weather events. USGS is working to develop an early warning system for landslides.
Signed evacuation routes	–
Conventional transportation signage (e.g., "Falling Rocks Next 2 Miles")	–
Changeable message signs (CMS)	Compared to conventional signage, CMS convey more information that also can be updated.
Information pamphlets	Can be distributed via mail and at various public spaces.
Public workshops	Especially in critical regions. More effective if combined with other methods marketing the event.
In-person seminars	High volume of information can be transmitted, but reach is limited.
Online webinars	Potential for greater outreach at less expense than in-person seminars. Can be recorded and posted to websites or through social media.
Email newsletters	–
Email announcements	Can be part of an alert system
Social media	Creative Twitter users have created accounts for sinkholes in their city and periodically send out tweets to notify the public of hazards.
Interactive, web-based GIS maps	Can document historical events, current risk levels, projected risk levels, and other information.
Conventional media (newspapers, radio, TV, magazines)	Can include technical experts' input for local and national stories.

5.3.1 Combined Avalanche, Landslide, Flood Risk Website in Norway

The Norwegian Public Roads Administration (NPRA) has a web-based system for communicating current avalanche, landslide, and flood risk levels to the public. The assessments, based on a simple 4-point scale, are displayed on a map at the website www.varsom.no (see Figure 5-9). Information from the website www.xgeo.no was discussed in Sections 5.1 and 5.2.

The Norwegian Water Resources and Energy Directorate uses this information to perform short-term risk assessments that are the basis for the public information.

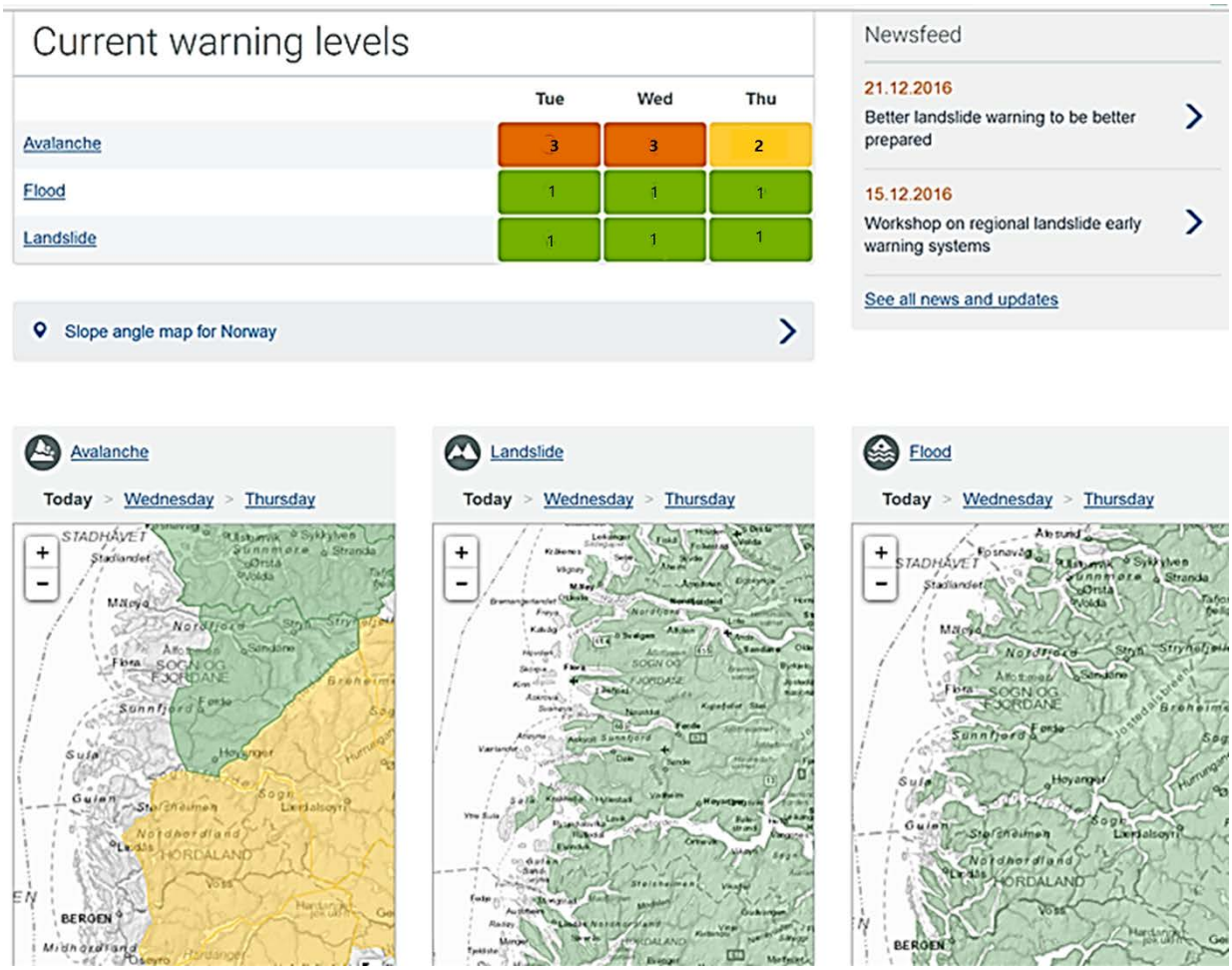

Figure 5-9: Example screenshot from www.varsom.no showing short-term risk assessments of avalanches, landslides, and floods in Norway.

5.3.2 Seismic Risk Assessment Website Prototype in Iran

Researchers at the Sharif University of Technology in Iran developed the Civil Infrastructure Risk Analysis website (http://cira.civil.sharif.edu) that facilitates assessing seismic risk for buildings in Tehran (Ghasemi et al. 2018). Visitors enter the location of their building and basic characteristics of the building (number of stories, construction type, age, etc.) to develop a tailored risk analysis. The output characterizes risk in terms of potential casualties and potential damage. To communicate the potential for casualties, the website compares the probability of earthquake casualties to the probability of a pedestrian dying after being struck by a car, with the speed of the car varying as a function of the building location and characteristics. The website also shows photographs of similar damage from previous earthquakes.

6 ADAPTATION ASSESSMENTS FOR INDIVIDUAL GEOTECHNICAL ASSETS

This chapter focuses on how to conduct climate change adaptation assessments for individual geotechnical assets. Under the assumption of a stationary (non-changing) climate, practitioners traditionally used to consult historical climate data, obtain a climate metric for use in design, and design their asset to that single value. But the many unknowns of climate change assessment call for a new approach. Single values no longer work. Instead, design options and costs should be evaluated across multiple plausible scenarios of future conditions.

FHWA's Adaptation Decision-Making Assessment Process (ADAP) is one of several frameworks for assessing and adapting transportation infrastructure to climate change (FHWA 2017, FHWA 2017c). The ADAP process consists of these 11 steps:

1. Understand the site context.
2. Document existing or future base case facility.
3. Identify climate stressors.
4. Develop climate scenarios.
5. Assess performance of the facility.
6. Develop adaptation options.
7. Assess performance of the adaptation options.
8. Conduct an economic analysis.
9. Evaluate additional considerations.
10. Select a course of action.
11. Develop a Facility Management Plan.

Figure 6-1 shows the decision flowchart for these 11 steps in the ADAP framework. The Adaptation Decision-Making Process is available in more detail from FHWA's website, https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework.

6.1 Overview of the Adaptation Decision-Making Assessment Process

ADAP is useful for new projects as well as assessments of existing facilities. For new projects, the process should be applied *after* an initial conceptual project design that uses historical climate data is developed and *before* a final design is selected. Typically, ADAP is used in the design stage of project development in conjunction with National Environmental Protection Act (NEPA) analyses.

ADAP can help determine whether to apply adaptations to address climate impacts. If so, which adaptation will perform best across the range of plausible future climate scenarios?

ADAP can apply to any type of geotechnical work involving climate data inputs (e.g., pavement design, slope stability analysis, permafrost thaw analysis). It can also be used by other engineering disciplines for their climate-dependent design elements (e.g., hydraulic design, structural engineering). Practitioners are encouraged to work across disciplines when applying the ADAP framework to obtain a holistic perspective on climate impacts and adaptation needs.

The process involves assessing the existing asset or proposed project against projected climate scenarios. If the projected climate scenarios are great enough to negatively affect the asset, the process calls for adaptation options to be developed to address the concerns. These adaptation options are then tested for effectiveness under various scenarios. After testing, an economic analysis is conducted to determine which option will be most cost-effective across the range of possible scenarios. At this point, additional (non-monetizable) factors are considered and a decision is made on the best design to use.

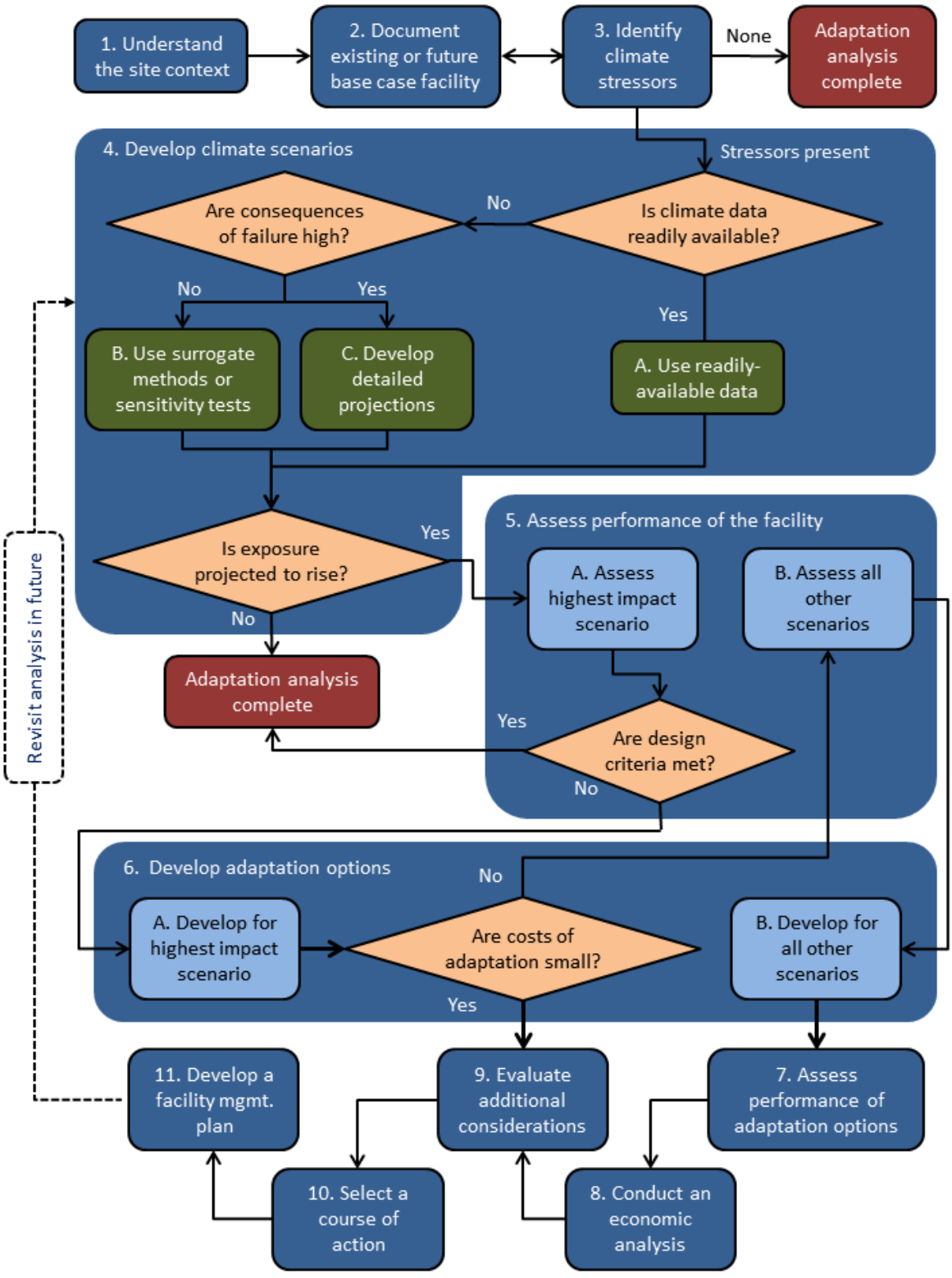

Figure 6-1: FHWA Adaptation Decision-Making Assessment Process (ADAP).

6.2 ADAP Step-by-Step

When working through the ADAP process, it is important to document the assumptions, findings, and decisions made at each step.

6.2.1 Step 1: Understand the Site Context

The first step in ADAP involves documenting the context of the project. Some key considerations are:

- **Environmental characteristics:** Include documentation of the regional geology, local hydrography, topographic features, land cover, etc. Any sensitive environmental resources in the area should be noted.
- **Community characteristics:** Include documentation of the surrounding land uses in the immediate vicinity of the project, and note important community facilities. Also note any residences nearby that may be affected by the project, as well as the demographics of those areas (incomes, racial composition, etc.).
- **The functional role of the transportation asset threatened by the geohazard in the broader transportation network, both today (if an existing asset) and in the future (if the importance of the asset may increase):** What locations does it link and how much redundancy is in the network should this asset be compromised? Mention any special roles played by the asset, like serving as an evacuation route or providing access to a hospital.
- **Performance characteristics of the threatened transportation asset:** Note information on traffic volumes, truck volumes, whether the asset is part of a bus route, and any other performance characteristics, including the potential deterioration of the asset.
- **Long-term transportation and land use plans for the area served by the threatened asset and how these may influence its functional role and performance characteristics:** Particularly in coastal areas, understand whether project plans consider sea level rise and the future habitability of the areas being served by the asset. Are there plans to protect the buildings in these areas or will the area eventually be abandoned? This can influence to what degree the asset should be adapted in later steps.

6.2.2 Step 2: Document Existing or Future Base Case Asset

Step 2 focuses on the transportation asset, its specific design characteristics and its condition. In this step, make a distinction between assessments for existing facilities and assessments for new projects. For existing assets, document the asset as it exists today. For new projects, document the new asset, *as designed in the traditional way using observed historical climate data* (referred to here as the "future base case asset"). A traditional design is used as the future base case asset to provide a test case to determine if climate change adaptation is necessary and, if so, whether it is cost-effective.

For geohazards, document all data typically used in a geotechnical analysis of the potential hazard in question, including design or performance standards. For example, an analysis of a steep slope along an existing roadway should include documentation of the slope's angle, any past movement of that slope, the soil types underlying that slope, and historical data on

groundwater levels. The section titled “Techniques for Documenting Slope Movements” on the next pages lists some remote sensing techniques for measuring slope movement.

Also in Step 2, describe any in-place mitigation measures for geohazards (e.g., a retaining wall and drains on a slope). Depending on the geohazard, also document the design of the transportation asset (e.g., pavement design for pavement foundation concerns, bridge design for bridge scour assessments, etc.). In the descriptions of the mitigation measure or transportation asset, include information about:

- **Design characteristics:** Include the type of design, dimensions, materials, location, existing subsurface conditions, etc.
- **Age and design life:** When was the mitigation measure installed or the asset built, and how long was it intended to last?
- **Condition:** Is the mitigation measure or asset in good condition or has it deteriorated or suffered other damage that might reduce its effectiveness?
- **Design criteria:** If the mitigation measure or asset was designed to be effective up to a certain threshold of geohazard severity (e.g., a 500-year flow event for scour or a slope factor of safety of 1.5), that threshold should be stated. Note if no design criterion was specified, that should also be noted.

A challenge for Step 2 is that key geohazards information is often not directly observable and can be underground. Thus, intensive fieldwork is often involved to collect the data. This fieldwork will likely occur as part of any new project. Assessments of existing facilities may entail new fieldwork for the adaptation analysis. The additional fieldwork can add time and expense to the adaptation analyses of some geohazards, such as landslides.

When data is limited, practitioners may choose to document all that is known and then proceed to Step 3 to conduct a parametric analysis to determine if the climate scenario presents a threat. If climate change does present a threat, practitioners can return to Step 2 (as indicated by the double-ended arrow between Steps 2 and 3 in Figure 6-1) and conduct additional fieldwork to perform a more detailed geotechnical analysis.

Techniques for Documenting Slope Movement

Several important measurement techniques can help identify geohazards and, in some circumstances, monitor their progress. Most of the techniques gather information about spatial position. Spatial position is three-dimensional, with two dimensions establishing the planar location on the ground surface and the third establishing elevation. Changes in spatial position—either elevation changes in time or abrupt elevation changes along the ground surface—can indicate movement associated with geohazards, including landslides, sinkholes, earthquakes, and subsidence. Movements at depth are also discussed below; such information is typically used to monitor the progress of landslides.

- **Remote Sensing:** Remote sensing techniques are used to survey objects from a distance. The source of remote sensing measurements can be ground-based, airborne (by plane or unmanned aerial systems [UAS]), or satellite-based. In many cases, multiple measurement sources can be used (e.g., ground-based and airborne). These techniques include photogrammetry, LIDAR, and radar. (The descriptions below are from Andrew et al. [2012].)
    - **Photogrammetry:** Photogrammetry involves identifying common points in photographs taken from multiple positions. The intersection of lines of sight from the known camera location to the common point is used to identify the point's three-dimensional location. Photogrammetry can be applied to a pair of ground-based images, but common application as a remote sensing technique involves a series of images taken by airplane or UAS and processed using sophisticated algorithms to produce terrain models. Anderson (2013) emphasizes the value of photogrammetry for mapping potentially hazardous landslide or rockslide sites using relatively inexpensive digital cameras.
    - **LIDAR:** LIDAR (an acronym of "light detection and ranging") uses the reflection of light pulses off the earth's surface to infer the distance between the source and the surface (using the speed of light). Typically, LIDAR is airborne and uses a scanning laser to send many pulses as the plane flies. The plane location is tracked using global positioning satellites (GPS) to facilitate calculation of the planar location of the inferred elevations. The primary advantage of LIDAR is relatively quick measurement of ground surface elevations for large swaths of land. The primary disadvantage is accuracy, which is mostly limited by the GPS component. Typically, accuracies of 6 inches (15.2 centimeters) vertically and sub-meter (less than 3 feet) horizontally are expected (Anderson 2013). Colorado DOT (CDOT) has used UAS to capture LIDAR data along corridors at high risk of rockslides. While LIDAR eliminates many of the errors resulting from use of a moving source and improves accuracy, lasers are expensive (Anderson 2013).

- **Radar:** Like LIDAR, radar sends a signal to the ground surface and the signal's reflection is measured to interpret distance. Radar uses electromagnetic radiation— microwave for most radar remote sensing applications—with a considerably longer wavelength than the visible light used in LIDAR. The long wavelength reduces atmospheric effects but uses large antennas to achieve adequate resolution. The phase difference between two radar images at the same location from two different times can be used to interpret displacement of the ground surface. The technique for interpreting the displacement from phase differences is known as interferometry.
  - **Interferometric Synthetic Aperture Radar (InSAR):** Satellite-based InSAR uses data from satellites that orbit the Earth on closer paths than those used for GPS. The distance traveled by the satellite during the time between pulse generation and return is used as a large antenna—the "synthetic aperture." Anderson (2013) reports the spatial resolution of the images is about 25 to 100 feet (7.6 to 30.5 meters), which is too large to identify some small geohazards. In addition, the time between satellite passes is about one month, likely too long for any monitoring application.
  - **Ground-based Interferometric Radar (GBIR):** The University of Missouri developed a ground-based radar system like the InSAR device, but with a real aperture in the form of an 8-foot-long antenna. The device was used to measure displacements as small as 0.02 inches (0.5 millimeters) along an unstable slope in Colorado (Rosenblad et al. 2016). The device has also measured similarly small displacements in a controlled study of rock movements.

- **Existing Databases:** It may be possible to detect movements by comparing spatial position information in existing databases. Comparisons may be made between new data and existing data, or between successive sets of historic data. However, comparisons may be subject to large potential errors depending on the resolution of the datasets and on differences in datum or other potential inconsistencies.

  USGS maintains The National Map, which contains elevation data within the 3D Elevation Program (3DEP). The information is primarily from LIDAR data. The resolution of the maps varies across the country, but 32.8-foot (10-meter) plan resolution is not unusual; some areas of the country have 3.3-foot (1-meter) resolution. The areas with greater resolution are being expanded as new LIDAR data becomes available. Additional datasets may be available on a State, region, or local basis, or from other agency databases such as pavement management system inventories. Regardless of the databases used to identify or characterize potential geohazards, the resolution of the information should be noted and considered in any interpretation.

- **Movements at Depth:** If a potential landslide is identified, it is possible to obtain more detailed site performance information by measuring profiles of soil movement with depth. The measurements can be used to monitor performance more precisely and reliably, and to gather information about the nature of sliding, such as the sliding depth. The measurements are typically collected by drilling through the sliding material and grouting in place a small-diameter casing. The tip of the casing should be embedded at a depth beyond the sliding surface sufficient to ensure fixity at the bottom of the casing.

Once the casing is installed, movement can be interpreted from measurements of casing inclination versus depth. Various systems are available to make such measurements. Personnel should be on site to lower and raise the probe in traditional inclinometer systems. Newer systems consist of a series of smaller probes that can be left in-place. Microelectromechanical systems (MEMS) devices have been introduced; fiber optic systems are also available.

Measurements of vertical movement versus depth can also be made. Such measurements may be useful for some geohazard applications, including subsidence. The casing installation process is like that for sliding measurements. The devices used to measure the change in vertical position at depth, extensometers, are displacement-based, rather than inclination-based as for the inclinometer systems.

6.2.3 Step 3: Identify Climate Stressors

In Step 3, the specific climate stressors that affect the asset's design and performance should be identified. Table 3-1 in Chapter 3, which lists the climate stressors related to different geohazards, may be helpful for this step. Multiple climate stressors may affect an asset. In such cases, all relevant climate stressors should be assessed to make a holistic assessment of impacts. In some cases, climate change can impact an asset indirectly through other impacts. For example, climate change may increase the probability of wildfire or insect infestations that kill trees on a steep slope. The reduction in tree coverage may increase the risk of mudflows and landslides. These indirect effects can be significant and should be considered in the analysis to the extent possible.

The relationship between a climate stressor and the hazard is not always immediately apparent. For example, some landslides may respond to increases in precipitation while others may not. As in Step 2, some analysis should be performed to determine the climate stressors that affect the asset. For landslides, if extensive field data is available over a long time, an analysis may be performed to determine if there is a relationship between ground movement and observed precipitation. If field data is more limited, practitioners can undertake a parametric analysis that looks at an extreme high groundwater elevation that saturates the entire slope. If the slope's factor of safety is not exceeded under this extreme situation, it can be concluded that precipitation is not an important direct climate stressor to the slope. If it is determined that no climate change-related parameters would ever threaten the asset, then the adaptation analysis can be concluded. However, if the factor of safety is exceeded, precipitation should be considered a potential climate stressor and a closer look should be taken at this climate variable in subsequent steps. In these cases, practitioners would return to Step 2 to collect more data on the asset. Factor of safety may not be the best indicator or metric of performance for the ranking of the cost-effectiveness of remedial measures, unless a factor of safety of 1.0 is used for an extreme event. Then the probability of failure can be evaluated against the consequences of failure in a more rational analysis.

6.2.4 Step 4: Develop Climate Scenarios

Step 4 involves developing projections for each stressor identified in Step 3. This step typically involves working with large datasets output from climate models. Many times, the standard outputs from the climate model (daily precipitation depth and maximum and minimum temperatures) should be manipulated to produce the specific climate metrics identified in Step 3. Practitioners should work with climate scientists familiar with the region in which the project is located if questions on climate projections arise.

As noted in Chapter 4, climate projections should be developed for at least two greenhouse gas emissions scenarios (RCPs 4.5 and 8.5), to bound the range of possible future conditions. This is the case for assets with longer design lives, as there is more divergence in the scenarios after the next 30 years. Adding a third scenario provides more information to use when designing adaptations and a richer set of outputs for decision-making. If resources allow, practitioners can test multiple scenarios using different combinations of emissions scenarios and climate models.

The period over which projections should be developed varies depending on if the asset is new or existing. For new assets, the period may coincide with the design life of the asset. For existing assets, the period should coincide with the asset's adaptation options. Developing projections over these periods ensures that adaptation options can be developed to handle the worst-case conditions to which the asset may be exposed. It also ensures that the economic analysis can consider the asset's full lifecycle costs. However, sometimes the design life of the asset may extend beyond the timeframe of available climate projections, which are typically only provided through the year 2100. If so, projections should be developed through the latest year they are available and a note added to the report.

Practitioners should develop projections at multiple horizon years over the project's lifespan, not just for the end of its lifespan. This will enable a richer understanding of how climate change may impact the asset over time and is necessary information for the economic analysis. In some cases, the maximum impacts of a climate stressor may not occur at the end of an asset's design life. Climate change and their impacts do not always get progressively worse. It is suggested that practitioners report projections at 30-year intervals during the asset's lifespan. The time intervals should be consistent to make interpretation of the results easier and to facilitate a more accurate economic analysis. However, the assessment of some geohazards will involve use of daily projections. For example, daily temperature data is used for permafrost thermal modeling. Thus, temporal needs will vary depending on the asset type and geohazards being studied.

There are different paths to take in Step 4 depending on data availability (as shown in Figure 6-1). If climate projections are readily available and in the appropriate format, use that data. If proper metrics are not readily available and the consequences of the asset's failure are high (in terms of safety; impacts to travel, including increasing cost to users; etc.), use available climate projections to calculate relevant metrics. If the proper metrics are not readily available and the consequences of failure are not high, it may suffice to use higher level generalized measures. For most geohazards applications, however, climate projections are readily available. Efforts should be made to transform them into the metrics used for analysis.

After developing climate projections, evaluate to determine if the projections are trending in a direction that might affect the asset. In some cases, the trend may be toward fewer impacts with climate change. If the trend toward exposure is downward under all the climate scenarios for all relevant climate metrics, then the adaptation analysis can be concluded. For example, in some locations, the number of freeze-thaw days and precipitation may decrease under projected climate scenarios, which could reduce the occurrence of rockfalls. If the adaptation analysis focuses on a rock slope along a roadway and freeze-thaw days and precipitation are determined to be the only relevant climate stressors, then the analysis can be ended here. No adaptations will be needed (today's conditions are controlling). Otherwise, proceed to Step 5.

6.2.5 Step 5: Assess Performance of the Asset

In Step 5, an engineering analysis is performed to determine whether the projected climate scenarios from Step 4 will be great enough to negatively affect the performance of the asset. This often involves some form of geotechnical modeling using climate projections. For example, thermal modeling using future temperature and precipitation projections may be conducted for a

road built on permafrost to determine if differential settlement will be an issue. Likewise, groundwater modeling that uses future precipitation projections may be conducted for a steep slope at risk of landslides to determine if the slope will exceed its design factor of safety.

For efficiency, ADAP suggests that practitioners first evaluate what they believe will be the highest impact climate scenario. As shown by the flow chart in Figure 6-1, this enables determination of any detrimental impacts to the asset. If there are no detrimental impacts even under the worst-case scenario, then there typically is no reason to evaluate the other scenarios. If there are detrimental impacts under the worst-case scenario, then it may be worth evaluating the other scenarios, especially if the incremental cost of adapting to the worst-case scenario is high. This logic is indicated by the flow path extending into Step 6 then back to Step 5 in Figure 6-1.

Practitioners should take care in determining the highest impact scenario. This may be the scenario with the most substantial change projected for the climate stressors of interest (typically, RCP 8.5). However, there are cases where a scenario that entails less change may be more impactful; this depends on the relationship between the climate stressors and asset. If there is any doubt about which scenario is most impactful, practitioners should evaluate all scenarios in Step 5 before proceeding to Step 6.

Whatever path is chosen, the conclusions on whether the relevant design standards are violated, and the implications, should be described for each scenario. The conclusions should also clearly state *when* the design standards may start to be violated (or become more likely to be violated), as this is critical information for adaptation planning and economic analysis (including road closures and detours that can add to travel time and related user costs). If the design standards are not violated under any of the climate scenarios, then the adaptation analysis can be concluded. However, if there are detrimental impacts, then practitioners should proceed to Step 6.

6.2.6 Step 6: Develop Adaptation Options

In Step 6, develop adaptation options and their associated cost estimates for each scenario where design standards were exceeded. Typically, adaptations are designed to ensure adequate asset performance under the worst-case conditions projected for each scenario. For example, if design standards for an asset are violated under the RCP 6.0 and RCP 8.5 scenarios in the late century, then separate adaptation options should be developed for the RCP 6.0 worst-case conditions. Develop other options for the RCP 8.5 worst-case conditions—these options will typically entail greater changes than for RCP 6.0. The number of adaptation options to develop is up to the practitioner, but there should be at least one for each impactful scenario. While it is more work to evaluate more options, the effort offers a greater chance of selecting the best option for the site. It is also likely that other limitations may exist so that implementing design for a worst-case condition would not be feasible. In this case, evaluate options that are reasonable, with the worst-case in mind for future work or phased adaptation.

Using this strategy, known as adaptive management (or “adaptation pathways”), an adaptation option does not need to be built out completely at the start. Adaptation options can be phased in over time, as observed conditions change to the point where certain predefined thresholds are reached that trigger action. This approach reduces the risk of an adaptation option being

constructed that later proves unnecessary if climate does not actually change to the extent envisioned by the designer, or if it and the needed adaptation are more severe than expected.

As shown in Figure 6-1 and mentioned in Step 5, adaptation options typically are most effective if they are first developed for the most impactful climate scenario. If the costs associated with the worst-case scenario are considered small by the agency, then the practitioner may decide immediately to go with that option and forgo the analysis of other scenarios and the economic analysis. In this case, the practitioner would skip immediately to Step 9, as shown in the flow chart. On the other hand, if the adaptation costs for the worst-case scenario are high, other scenarios should be evaluated and adaptations options developed; there may be another option that proves more cost-effective across the possible scenarios.

Many adaptation strategies are available to deal with the geohazards discussed in this report. Table 6-1 lists some possible strategies that practitioners can consider for each geohazard. Note that this table is a starting point for thinking through different options and is not intended to be a comprehensive list of all strategies. Other strategies can be found on the Geo-Institute[10] website, GeoTechTools.

[10] The Geo-Institute is a membership organization focused on geo-professionals and the geo-industry. It was created by the American Society of Civil Engineers (ASCE) in October 1996 as one of ASCE's specialty Institutes.

Table 6-1: Examples of Adaptation Strategies for Addressing Various Geohazards

Geohazard	Adaptation Strategies
Landslides, earthflows, and debris flows	• Improve drainage • Reduce slope height or inclination • Anchors or anchored walls • Gravity walls • Mechanically stabilized earth (MSE) walls • Soil nailed walls • Piles or drilled shafts • Catchment fences • Sediment basins • Lime stabilization • Cement grouting • Increased vegetation • Thermal treatment • Geogrids or geotextiles • Bio-geotechnics
Rockfalls/topples	• Rock bolts/anchors • Shotcrete • Barriers • Flexible wire mesh systems • Fences • Ditches • Flattening or scaling of slope
Consolidation and expansive soils	• Ground improvement through: o Grouting o Soil mixing o Compaction o Placing fill o Pre-loading • Deep foundations • Drainage
Dust storms	• Improved alert systems
Earth fissures	• Routing drainage away from fissures • Avoiding groundwater pumping
Karst features	• Grouting
Permafrost melting	• Insulation below road surface • Air convective embankments • Thermosyphon heat pipes

Geohazard	Adaptation Strategies

Seismic-induced liquefaction, lateral spread, surface rupture, and ground shaking	• Excavation and compaction
	• Densification through:
	  o Vibratory probes
	  o Heavy tamping
	  o Piles
	  o Blasting
	  o Compaction grouting
	• Ground improvement through:
	  o Grouting
	  o Vertical drains
	  o Pre-loading
	  o Soil mixing
	  o Deep foundations
	  o Reinforced shallow foundations
	• Surface rupture can be addressed through:
	  o Extending seat length
	  o Flexible link elements in superstructure
	• In coastal areas, lateral spreading can be contained through:
	  o Berms
	  o Dikes
	  o Sea walls

Scour erosion	• Concrete block system • Grout-filled mattresses • Gabion mattresses • Rock riprap • Green/vegetated slope • Embankment stabilization • Grout/cement filled bags • Soil cement • Adding deeper foundations • Dikes or other river-training structures
Coastal erosion/cliff retreat	• Increased vegetation • Sea walls • Gabion mattress • Piles or drilled shafts • Grouting • Shotcrete

6.2.7 Step 7: Assess Performance of Adaptation Options

Step 7 of ADAP is very much like Step 5. In Step 7, the performance of the *adaptation options*, rather than the existing or future base case asset, are evaluated under each climate scenario. This provides information on how effective each adaptation option would be if a climate scenario other than the one designed for happens; this is critical information for economic analysis and decision-making. For example, if three climate scenarios are being evaluated (RCPs 4.5, 6.0, and 8.5), how would the adaptation option designed for RCP 4.5 fare if RCPs 6.0 or 8.5 occurred? As in Step 5, the approximate date of any projected impacts and their implications should be noted.

6.2.8 Step 8: Conduct an Economic Analysis

In Step 8, an economic analysis of the adaptation options is conducted to determine: (1) if any of the adaptation options are cost-effective and (2), if so, which option is the most cost-effective. Adaptation economic analyses are often structured using a benefit-cost framework, where costs represent the incremental costs of building and maintaining the adaptation option (estimates of which were developed in Step 6) and benefits are the damage/cleanup, maintenance, and socioeconomic costs *avoided* by undertaking the adaptation. The product of an adaptation economic analysis is a table of benefit-cost ratios (BCRs), net present values (NPVs), and total lifecycle cost estimates for each adaptation option under each climate scenario. This information is invaluable for decision-making and allows one to determine if the additional up-front costs of the adaptation option are justified. Using the table of BCRs, NPVs, and/or total lifecycle costs, decision-makers can determine the adaptation option that performs best across the range of possible climate scenarios.

A challenge in conducting an adaptation economic analysis can be quantifying the benefits from each adaptation option. The approach differs depending on whether the climate stressor involved is chronic or acute. Chronic climate stressors are those that change slowly but continuously over time, such as temperature impacts to a roadway built on permafrost. Acute climate stressors, on the other hand, are those that happen periodically in discrete events, such as fires, extreme rainstorms, or landslides. For chronic climate stressors, benefits are captured by the reduced routine maintenance costs from the adaptation. Quantifying the benefits of adaptation for acute stressors is more complicated and includes estimating the number and severity of extreme events the asset will experience over its lifespan and the damage/cleanup, user costs, detours, closures, and socioeconomic costs saved by the adaptation. The costs saved can then be discounted and tallied over the asset's lifespan to estimate the cumulative cost benefits of the adaptation option.

To calculate the costs incurred during a weather event, the storm event's magnitude should be tied to impacts on the asset and consequence costs. These linkages can be captured through a graph known as a climate stressor-damage function. This graph shows the relationship between the severity of a climate stressor on one axis (typically the horizontal axis) and the dollar value of damage on the other axis (typically the vertical axis). The graph indicates how the asset will perform under different levels of a climate stressor and the consequences of failure. Each asset and adaptation option has its own unique function depending on its design and characteristics. Figure 6-2 shows an example climate stressor-damage function for an existing culvert (the Base Case). The figure also shows adaptation options that involve successively larger culvert openings

(Options 1 and 2) or a replacement bridge (Option 3). A similar function could be with different climate stressors for a steep slope or another geotechnical asset and its adaptation options. More information on climate stressor-damage curves can be found in FHWA's *Synthesis of Approaches for Addressing Resilience in Project Development* report ("*Synthesis* report").[11]

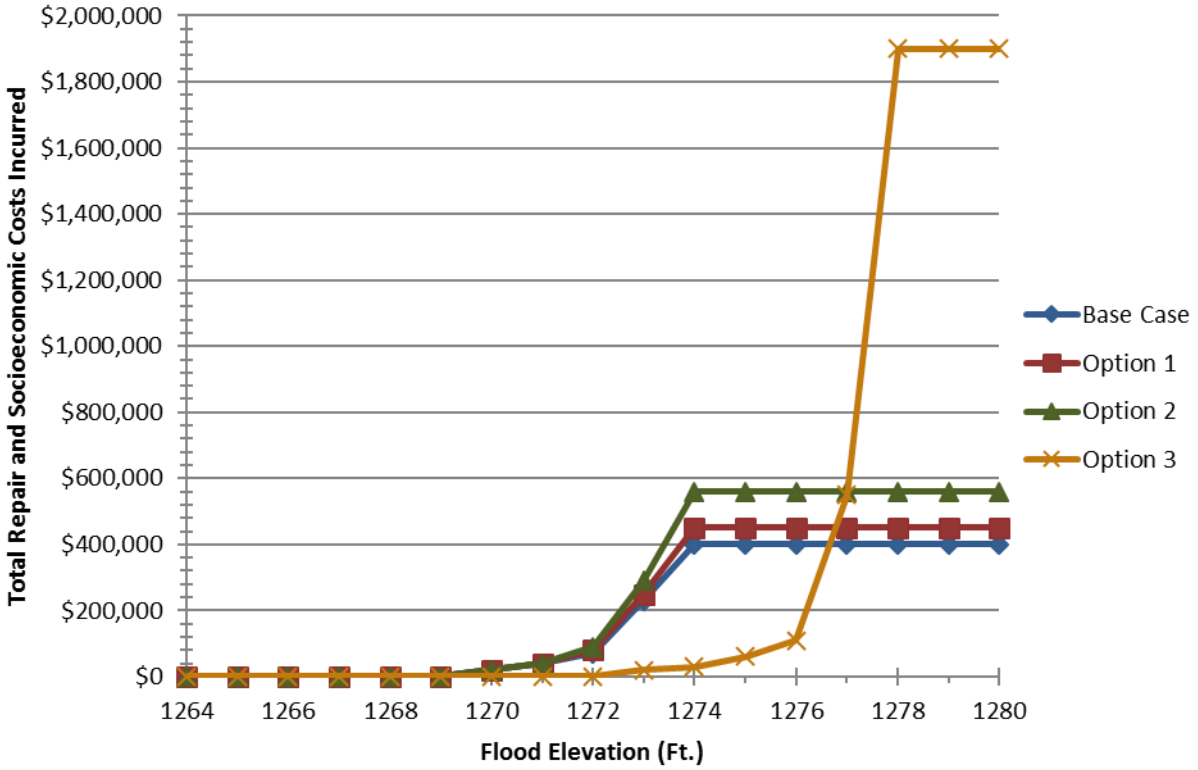

Figure 6-2: Example Climate Stressor-Damage Relationship Curves, MnDOT Culvert 5722 and its adaptation options.

Source: MnDOT 2014.

Once climate stressor-damage functions are developed for each design option, the next step in calculating benefits (the cumulative impact costs avoided) is to estimate the number and severity of damaging events the asset may experience over its lifespan. This should be done using information on the probability of the event happening under each climate scenario. For some climate stressors, such as extreme precipitation, developing probability information conditional on a given climate scenario is relatively straightforward. When probabilities are known, a Monte Carlo analysis or area-under-the-curve analysis can be run using the probability data, along with the climate-stressor damage function, to determine the cumulative damage costs. More information on how this is done can be found in FHWA's *Synthesis* report.

Estimating the probability of other types of acute events is less straightforward. For example, estimating the probability of a landslide of a certain volume occurring in a particular year given

[11] FHWA 2017

changing precipitation patterns can be challenging, particularly if a long record of slope movement in response to rainfall is not available. If probability information cannot be easily generated, the analysis can be set up using a "scenarios approach," where the timing and magnitude of events is determined by the project team a priori. The FHWA *Synthesis* report provides more details on this approach. A case study showing how the scenarios approach can be applied to a landslide can be found in the "Alaska Climate Trend Vulnerability Study."[12]

Once benefits are calculated, such as cumulative damage costs avoided (including user costs), they can be compared to the incremental costs of adaptation using the Benefit Cost Ratio and Net Present Value (BCR, NPV), or total lifecycle cost metrics previously described. The whole process should be repeated for each adaptation option and each scenario, so having a template for efficiently making the calculations repeatedly is helpful.

6.2.9 Step 9: Evaluate Additional Considerations

While economic analysis provides critical information for decision-making, some important project considerations cannot be monetized. Step 9 looks at some of these factors to select an appropriate course of action. Items to consider include:

- Environmental impacts
- Impacts to cultural resources
- Environmental justice concerns
- Public engagement on the various design alternatives
- Funding availability and tradeoffs

Note that this is not intended to be a comprehensive list of all considerations. Each project will have a unique set of factors to consider.

6.2.10 Step 10: Select a Course of Action

In Step 10, a decision is made on whether to make an adaptation and, if so, which option to choose. This decision should be arrived at after careful consideration of the economic analysis results and the additional considerations discussed in Step 9.

6.2.11 Step 11: Develop a Facility Management Plan

The final ADAP step develops a facility management plan to inform long-term facility management activities. The plan may include predetermined detour routing if the asset were to be compromised. Long-term monitoring activities, such as implementation of a method to monitor slope movement, may be included in the plan as well. If the chosen adaptation option takes an adaptive management approach, the plan may include specification of certain trigger thresholds for various climate metrics that encourage certain actions to be taken. The plan may also include provisions to revisit the analysis at a future date when new climate projections are available. The facility management plan should be a living document that is updated as needs and conditions change. All relevant elements of the facility management plan should be integrated into the agency's asset management program.

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[12] FHWA Western Federal Lands Highway Division and Alaska Department of Transportation & Public Facilities, 2016

7 USE OF GEOTECHNICAL ASSET MANAGEMENT IN GEOHAZARD PROGRAMS

The term "asset management" means a strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on both engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the lifecycle of the assets at minimum practicable cost (23 U.S.C. 101(a)(2)).

Since the 1980s, FHWA and State agencies have developed practices for transportation asset management (TAM), with contributions from consultants and academia. Early efforts focused on management of pavement systems and bridge inventories. Today, most agencies have implemented relatively robust systems for management of pavement and bridges. The Moving Ahead for Progress in the 21st Century Act of 2012 (MAP-21) requires agencies to utilize asset management systems to analyze the condition of NHS pavements and bridges. However, use of these management systems for other assets in the transportation asset management plan (TAMP) is optional (23 CFR 515.7). Regulations published in 2016 required States to identify a range of risks, including climate change related risks (23 CFR 515.7). More recently, Section 11105 of the Bipartisan Infrastructure Law, enacted as the Infrastructure Investment and Jobs Act, Pub. L. 117-58 (Nov. 15, 2021) amended 23 U.S.C. Section 119(e)(4) to require State DOTs to consider extreme weather and resilience as part of the lifecycle planning and risk management analyses within a TAMP (FHWA 2022b). Comprehensive asset management programs include geotechnical assets and assess hazards and risks to maintain a resilient and safe transportation network.

Management of geotechnical assets has received considerably less attention than management of pavements and bridges, but the concept of geotechnical asset management (GAM) has gained traction in recent years. TAM practitioners have realized the importance of managing all assets within the right-of-way, not just pavements and bridges. Another significant motivation for GAM is a recognition among some geotechnical engineers that TAM principles may help with the challenges of maintaining geotechnical assets. Geohazards are among the most significant challenges associated with management of geotechnical assets; indeed, two States that have pioneered GAM efforts, Alaska and Colorado, also contend with considerable geohazard threats. This chapter introduces GAM, discusses the relationship between geohazards and GAM and TAM systems, presents methods for condition assessment, and closes with a description of ongoing GAM efforts within the transportation community.

7.1 Introduction to GAM and Primary Challenges for GAM

The premise of the GAM systems that have been introduced, e.g., in Alaska (Landslide Technology 2017; Thompson 2017) and Colorado (Vessely et al. 2015; Cambridge Systematics, Inc. 2013), is not fundamentally different from other TAM systems. An overview of the Alaska Department of Transportation and Public Facilities' (AKDOT&PF) GAM process is shown in Figure 7-1. The steps can apply to virtually any type of transportation asset. Three critical

aspects that distinguish GAM from other TAM systems and present challenges to GAM implementation are: (1) determining the geotechnical assets to be included in the inventory, (2) assessing the condition of geotechnical assets and developing models for their performance, and (3) evaluating treatment options. Developing models of a probability or frequency of failure to assess cost-effectiveness can be a major challenge. Despite these challenges, several agencies have implemented GAM systems that include multiple asset types and consideration of geohazards in a risk-based framework.

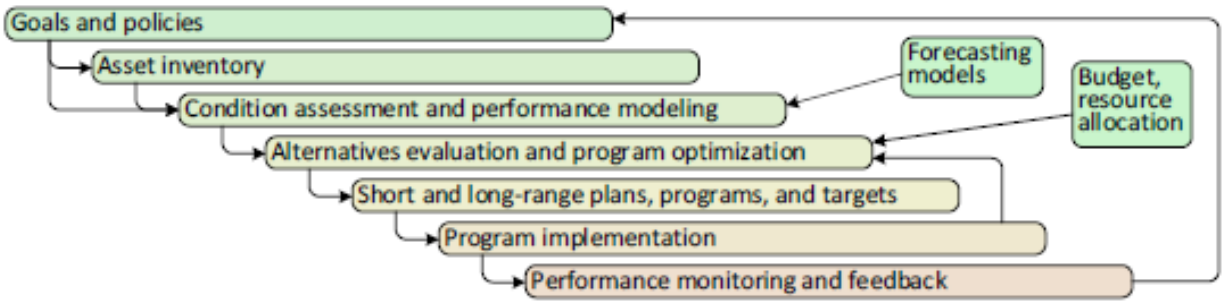

Figure 7-1: AKDOT&PF GAM process.

Source: Thompson 2017.

Geotechnical assets come in a variety of types, are often part of a larger transportation asset (e.g., a drilled shaft foundation that supports a bridge), and frequently lie outside the right-of-way. It is therefore complicated to determine which assets to manage through GAM systems. Anderson et al. (2016) suggested a taxonomy to address these complications (see Figure 7-2). The relatively large number of geotechnical asset types, such as retaining walls, slopes, and subgrades, is reflected by the size of the taxonomy. The taxonomy further breaks down geotechnical asset types by material, for example, rock slopes versus soil slopes. To distinguish geotechnical assets that serve as components of a larger transportation asset from geotechnical assets that stand alone, Anderson et al. (2016) apply the term "geotechnical element" to the former group. For assets outside the right-of-way, they apply the term "geotechnical feature."

Condition assessment and performance modeling are also complicated for geotechnical assets. Assessing condition can be challenging because typically only a small portion of a geotechnical asset is visible and accessible from the ground surface; the rest is below grade. For some geotechnical assets, ground-surface data is valuable performance information. For instance, deformation of the ground surface is a good indicator of slope performance, and deflection and cracking of a retaining wall face is a similarly good indicator of wall performance. Additional information about condition assessment is presented later in this chapter.

The difficulty of performance modeling is captured by Figure 7-3 (Sanford Bernhardt et al. 2003). The plot on the left is a conceptual representation of the form of performance model typically employed in pavement management systems; the plot on the right is a conceptual performance curve for an embankment on soft ground, which initially improves as the soft

ground consolidates, but then deteriorates with time as the embankment controls and is subject to deterioration, e.g., from surface erosion. Such a deterioration model is difficult to predict for any given embankment, let alone a system with many different embankments. Moreover, the model for other types of geotechnical assets—even other types of soil slope assets—is likely different from that shown in Figure 7-3(b).

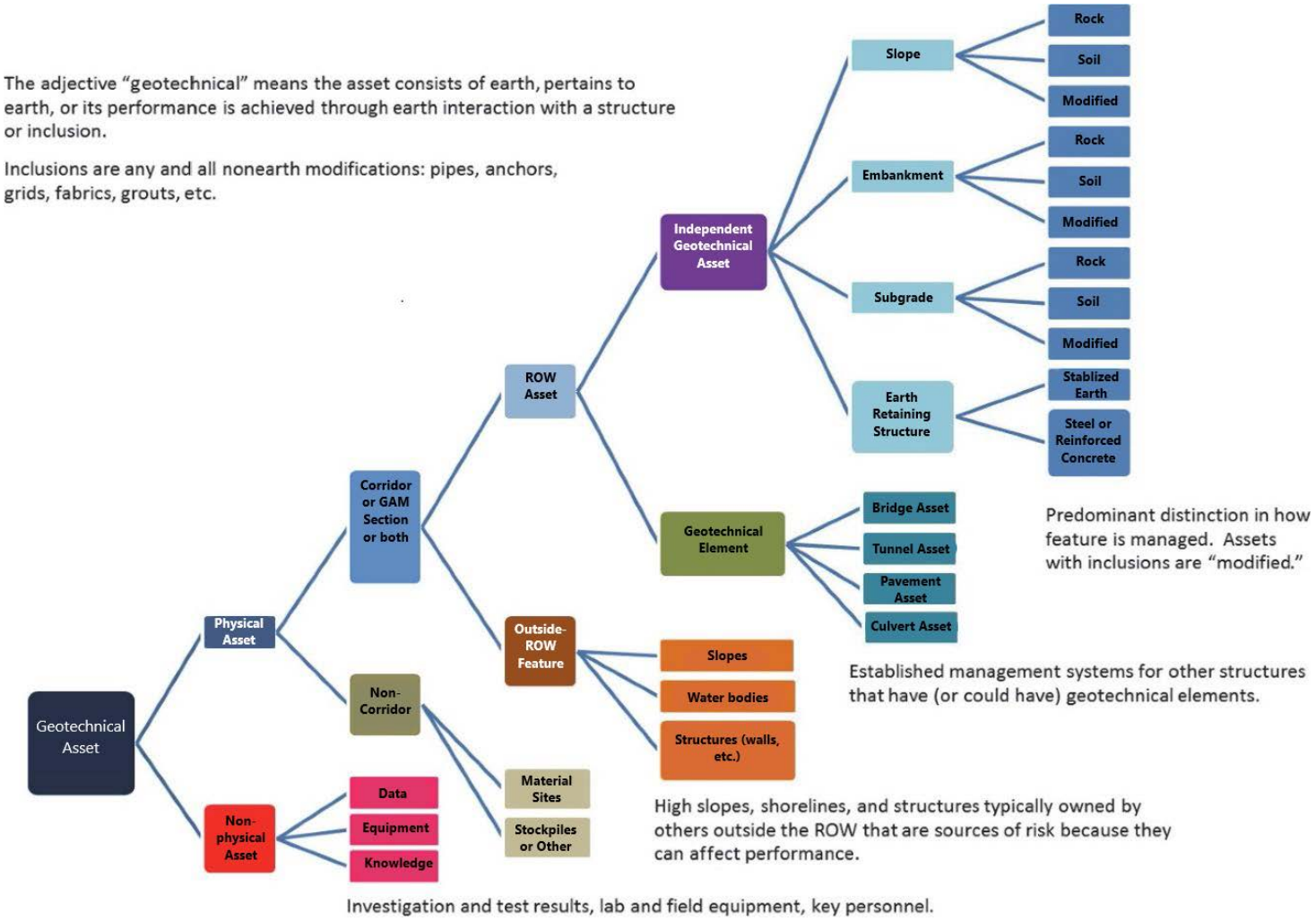

Figure 7-2: Taxonomy of geotechnical assets, elements, and features.

Source: Anderson et al. 2016.

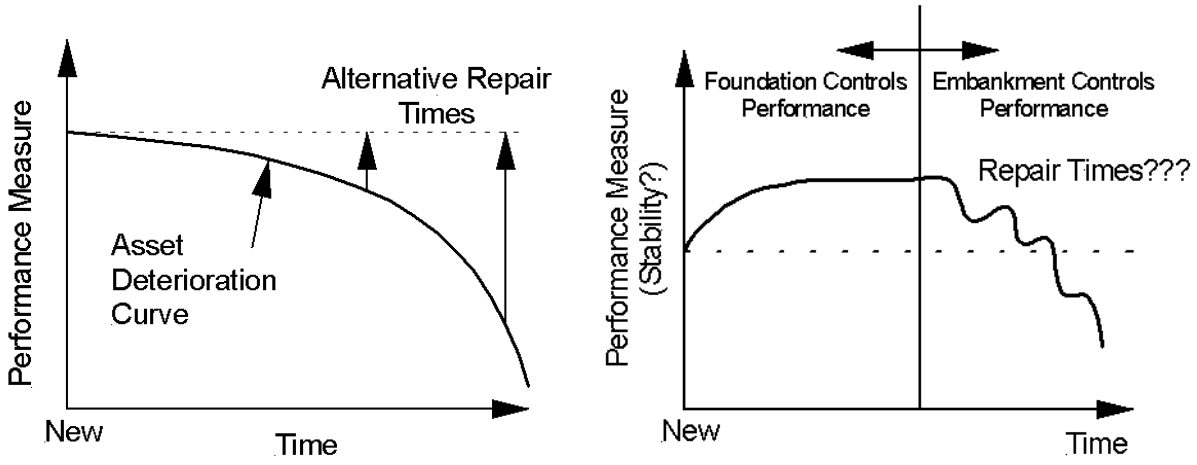

Figure 7-3: (a) Common form of asset deterioration model presumed in asset management systems for pavements, and (b) conceptual asset "deterioration" model depicting postulated performance of embankments on soft foundations.

Source: Sanford Bernhardt et al. 2003.

It is difficult to evaluate treatment alternatives when there is great uncertainty in the underlying performance model or the performance metric. For example, factor of safety does not directly relate to the probability of unsatisfactory performance. The impact of various treatment types on asset condition adds another uncertainty. The GAM system of AKDOT&PF includes a performance model for rock slopes. The model in Figure 7-4 is shown with several treatment options: doing nothing, or waiting until some level of deterioration has occurred before reconstructing the slope. (Note that the level of deterioration may not be a predefined threshold; the value may also depend on budgetary constraints, the condition of other assets in the system, and other GAM inputs.) Another alternative is multiple preservation treatments during the life of the slope prior to complete reconstruction.

The baseline deterioration model shown in Figure 7-4 is based on five essentially qualitative condition states assigned to rock slopes by AKDOT&PF. Numerical condition indices are assigned to the five condition states, with a line connecting the indices based on a Markov model. Time inputs for the model are not available from existing condition datasets, so a panel of experts was polled to assign times for transitions among the five condition states. As one of the first quantitative deterioration models for geotechnical assets, the AKDOT&PF performance model for rock slopes is an important contribution to the development of GAM frameworks. However, little to no data exists to validate the model, for obvious reasons given the scale of the horizontal axis. Collecting data to develop and validate performance models for geotechnical assets should be an important objective as agencies move toward GAM implementation.

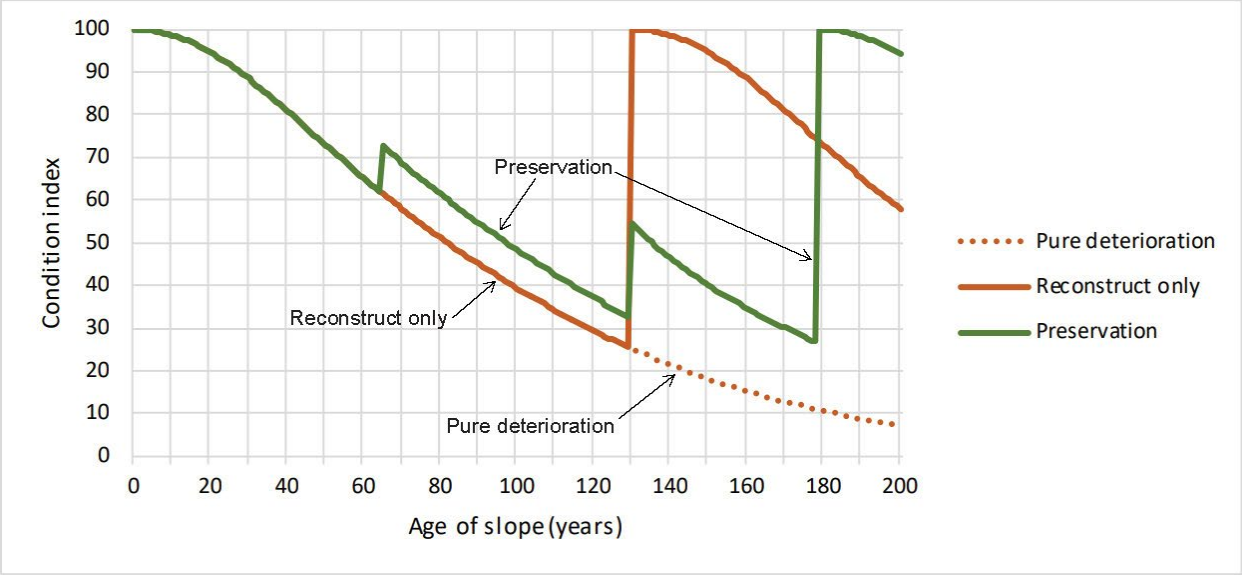

Figure 7-4: Deterioration curve for rock slopes with two alternative treatment options: reconstruct and preservation treatments prior to reconstruction.

Source: Thompson 2017.

The alternative treatments evaluation shown in Figure 7-4 is consistent with the evaluation methods typically employed for management of pavement and bridge assets. Frequently, such evaluations employ lifecycle cost analyses of the various treatment alternatives. The AKDOT&PF GAM framework includes a lifecycle cost analysis based on curves such as those in Figure 7-4. However, Alaska's GAM framework adds an evaluation not strictly included in traditional transportation asset management systems: risk assessment. The risk assessment is intended to address the consequential service disruptions that accompany failure events associated with geotechnical assets. AKDOT&PF's GAM framework considers likelihoods of service disruptions based on condition states. Consequences of service disruptions, including costs associated with accidents and mobility impacts, are based on the American Association of State Highway and Transportation Officials (AASHTO) "Red Book" (AASHTO 2010). Additional details of the risk assessment are provided by Thompson 2017.

7.2 Relationship between Geohazards and Asset Management

The risk assessment employed by AKDOT&PF's GAM framework is similar to the rockfall and landslide hazard rating systems discussed in Chapter 5. A primary difference between conventional, deterioration-based asset management and system-wide management of geohazards is the nature of the threats. Whereas conventional asset management is performance-based, accounting for consequences associated with continuous deterioration of all assets, management of geohazards considers events that occur at unique points in space and time, likely not affecting most assets but affecting certain others, often in a highly consequential manner. The analytical tools supporting each form of management reflect the nature of the threats. Analysis supporting conventional asset management is typically based on performance curves (e.g., Figure 7-3a), whereas analysis of geohazards involves probabilistic risk assessment.

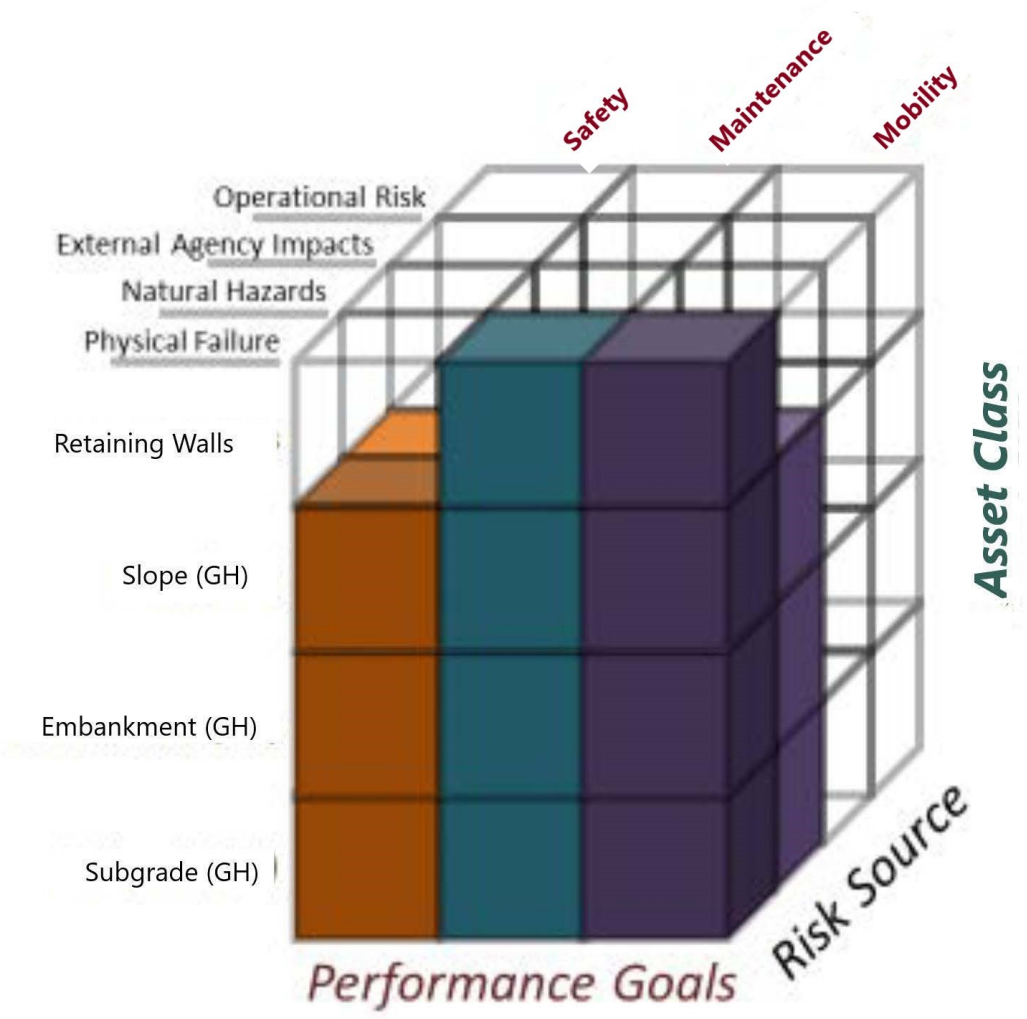

Figure 7-5: Risk cube identifying components of CDOT's GAM framework.

Source: Anderson et al. 2017.

The GAM program implemented by the Colorado DOT (CDOT) includes management of risks due to threats from deterioration and geohazards. Anderson et al. (2017) summarize the program's components via the risk cube shown in Figure 7-5. The risk cube concept was introduced in Chapter 5 of this manual. The CDOT risk cube in Figure 7-5 is based on four types of assets: (1) retaining walls, (2) slopes, (3) embankments, and (4) subgrades. The cube is also based on CDOT's three primary performance goals: safety, maintenance, and mobility. The 11 elements on one side of the cube represent risks due to "physical failure," the term Anderson et al. apply to the performance-based deterioration described above, with safety impacts due to physical failure of retaining walls deemed negligible. CDOT evaluates physical failure risks of retaining walls using condition data from the National Bridge Inventory with interpretation rules established via expert opinion. Consequences are based on agency maintenance costs and traffic data. Additional details of the program are described by Anderson et al. (2017) and Vessely et al. (2015). Like the AKDOT&PF GAM framework for rock slopes presented in the previous section, the CDOT GAM framework for deterioration of retaining walls is an example of how to

systematically manage deteriorating geotechnical assets in a rational manner using existing agency data. It is also noteworthy that CDOT's GAM framework for deterioration of retaining walls is both performance-based and probabilistic.

The second vertical layer of elements within the risk cube shown in Figure 7-5 represents geohazards risks. The CDOT geohazard management program consists of more than 1,600 roadway segments with documented prior geologic events. About half of the segments are associated with rockfall. Risk calculations for the geohazards are conducted according to the inputs listed in Table 7-1. The likelihood of failure for each segment is based on the past frequency of events but reduced for some segments to account for the likelihood that an event would impact safety, mobility, or maintenance goals. Consequences are also based on historic records of impacts. Additional details are provided by Anderson et al. (2017). CDOT's geohazards management system is also GIS-based, which allows the agency to identify "geographic concentrations of risk." Anderson et al. anticipate identification of the concentrated risk pockets will produce efficiencies via "management corridors" for risk-reduction projects.

Table 7-1: Summary of Inputs for Geohazards Risk Assessment within CDOT's GAM Framework, based on Anderson et al. (2017).

Risk Source	Likelihood	Consequence
Safety	Number of recorded events for each analysis segment	Number and severity of accidents per event, with three levels of severity
Maintenance	Number of recorded events for each analysis segment	Four levels of maintenance impact severity
Mobility	Number of recorded events for each analysis segment	Time of closure (five levels) and traffic counts

Although CDOT's geohazards management program was developed concurrently with its GAM framework, the consequences considered in the geohazards management program, which include safety, maintenance, and mobility impacts, are not strictly geotechnical. The CDOT geohazards management program is part of a larger risk-based TAM framework. The advantage of such a geohazards management framework is that it considers impacts throughout the agency's operations. Accordingly, there is no need for special consideration of geohazards within each asset-class-based TAM system that an agency has already established. If the consequences are described appropriately, the impacts of geohazards on the pavement system, bridge system, etc., can be considered collectively.

7.3 Condition Assessment Techniques

Effective asset management can be difficult without current and historical information about the condition of the assets to be managed. Collection of such information is referred to as "condition assessment." Condition assessment is generally a challenge for TAM, but it is especially challenging for GAM because the methods of condition assessment vary from one type of geotechnical asset to the next. Most of the assets are located at least partially below ground. Difficulties associated with condition assessment, particularly network-level assessment, are a significant impediment to implementation of GAM, but the problem is not intractable. A wide

variety of investigation techniques, such as conventional geotechnical investigation, geophysical methods, and remote sensing techniques (see details in the Chapter 6 section, "Techniques for Documenting Slope Movement") can be used to perform condition assessment of geotechnical assets. The key for GAM practitioners is to be familiar with the available investigation methods and their limitations, and to identify the appropriate method or methods for each condition assessment application.

Bridge foundations are a class of geotechnical assets (or geotechnical elements, following the 2017 Anderson taxonomy) for which condition assessment techniques are relatively well-established. Techniques are frequently applied when the foundation for an existing bridge is being considered for reuse, for example when the superstructure is being replaced. Although it is not always possible to assess bridge foundation conditions using available techniques, many investigation methods are available. Investigation methods include evaluation of agency historical records, such as construction plans, installation records, and inspection reports; excavation to expose the foundation; concrete core drilling and laboratory testing (e.g., core through a shallow foundation to inspect concrete and test its strength); and geophysical methods (e.g., pile integrity tests). The National Cooperative Highway Research Program (NCHRP) Synthesis 505, *Current Practices and Guidelines for the Reuse of Bridge Foundations* (Boeckmann and Loehr 2017) provides additional details on each of the methods. FHWA's *Application of Geophysical Methods to Highway-Related Problems* (Wightman et al. 2004) is also a useful reference.

Condition assessment techniques for retaining walls include visual observations and displacement measurements. Visual observations can be captured in inspection data supporting the National Bridge Inventory records, as in CDOT's GAM program described in the previous section. Measurement of retaining wall displacement is typically only performed for walls with observed or suspected performance problems. Most displacement measurements involve conventional survey techniques, but some remote sensing techniques can be applied to retaining walls. Remote-sensing techniques were presented in the Chapter 6 discussion of documenting the existing base case. Measurement of the displacement within retaining wall backfill (e.g., from telltales or extensometers) can also provide useful condition data, but such measurements are difficult to make without preconstruction planning. There are many other potential sources of retaining wall condition data, all of which are specific to certain wall types and circumstances. Examples include corrosion data for steel reinforcement within a concrete wall or mechanically stabilized earth wall and force data for walls with anchors or tiebacks.

Visual observations and displacement measurements are also the basis for condition assessment of slopes. Important slope performance information can be gathered visually, including observations of groundwater seepage and indications of displacement such as cracking, sloughing, and raveling. As for retaining walls, measurement of displacement for slopes is often based on conventional surveying. The discussion of remote sensing techniques in Chapter 6 focused on slopes and rockslides; the inclinometer methods for measuring displacement at depth (also discussed in Chapter 6) are also intended for slope applications.

For all geotechnical assets, maintenance records can provide valuable condition data. For example, pavement segments that are patched frequently may have subgrade issues. Or settlement may occur of a bridge foundation or embankment. Records of geomaterial removal, generally material eroded from a soil slope or fallen from a rock ledge, are especially important for assessing the condition of soil and rock slopes. Such information is useful for evaluating the probabilities of slope failure within the context of geohazards management. Locating, organizing, and, ideally, digitizing historic records of maintenance is a challenge for many agencies. However, ready access to the information is beneficial for geohazards management and likely many other agency functions.

Advancements in sensor technology provide opportunities to improve geotechnical condition assessment. For instance, "smart" foundations with sensors to measure loads, displacement, and corrosion would provide condition information that is unobtainable for most existing foundations. The cost of implementing instrumentation is frequently difficult to justify on a project-level basis. But the benefits for future agency decision-making, including within GAM programs, provides additional justification that should be considered. Sensor improvements associated with fiber optics and reduction of sensor costs may also make instrumentation and monitoring programs more practical for future condition assessment.

7.4 Geotechnical Asset Management Efforts

GAM is still in the early stages of development compared to asset management for pavements and bridges, but efforts are underway to advance the maturity of GAM frameworks.

The National Cooperative Highway Research Program published a GAM implementation manual for transportation agencies (NCHRP 2018). The goal of the project was to produce a manual that will help agencies incorporate geotechnical assets into TAM. The manual includes suggestions for managing geotechnical assets consistent with AASHTO TAM principles, examples of successful GAM frameworks, terms and taxonomy for geotechnical assets, performance-based principles for GAM, and methods for considering risk analysis within GAM. Use of the manual is voluntary and not a Federal requirement.

TRB has a subcommittee, AKG00(1), dedicated to GAM, which is jointly supported by the Geo-Environmental and Climatic Impacts on Geomaterials (AKG30) and the Geology and Geotechnical Engineering (AKG00). The subcommittee website (http://trb-gam.weebly.com) includes presentations and other key information from the subcommittee's meetings during the annual TRB conference.

7.4.1 Related Technology Efforts

Both AKDOT&PF and CDOT have initiated programs that harness mobile and web-based technology to facilitate GAM data collection. AKDOT&PF includes on its website an "event tracker," which is a GIS-based tool to view recorded geohazard events. A screenshot of the tool is shown in Figure 7-6. Geohazards stored in the tool include debris flows, floods, landslides,

wall failures, rockfalls, and others. By clicking on each event, users can view additional information, including cost, severity, and action taken.

CDOT has implemented mobile apps for field data collection supporting GAM inventory maintenance and condition assessment, including retaining wall inspections as shown in Figure 7-7. The application is also used to record information about geohazard events. Users of the mobile application, who include geotechnical and maintenance staff, can take photographs to support condition assessment and geohazard event data collection efforts. The photographs are georeferenced. The mobile application interfaces with a corresponding desktop application. Vessely et al. (2015) reported the software has greatly reduced the costs associated with data collection. In addition to mobile data collection, CDOT uses unmanned aerial systems (UAS) to collect LIDAR data in corridors at high risk of rockslides, as noted in Chapter 6.

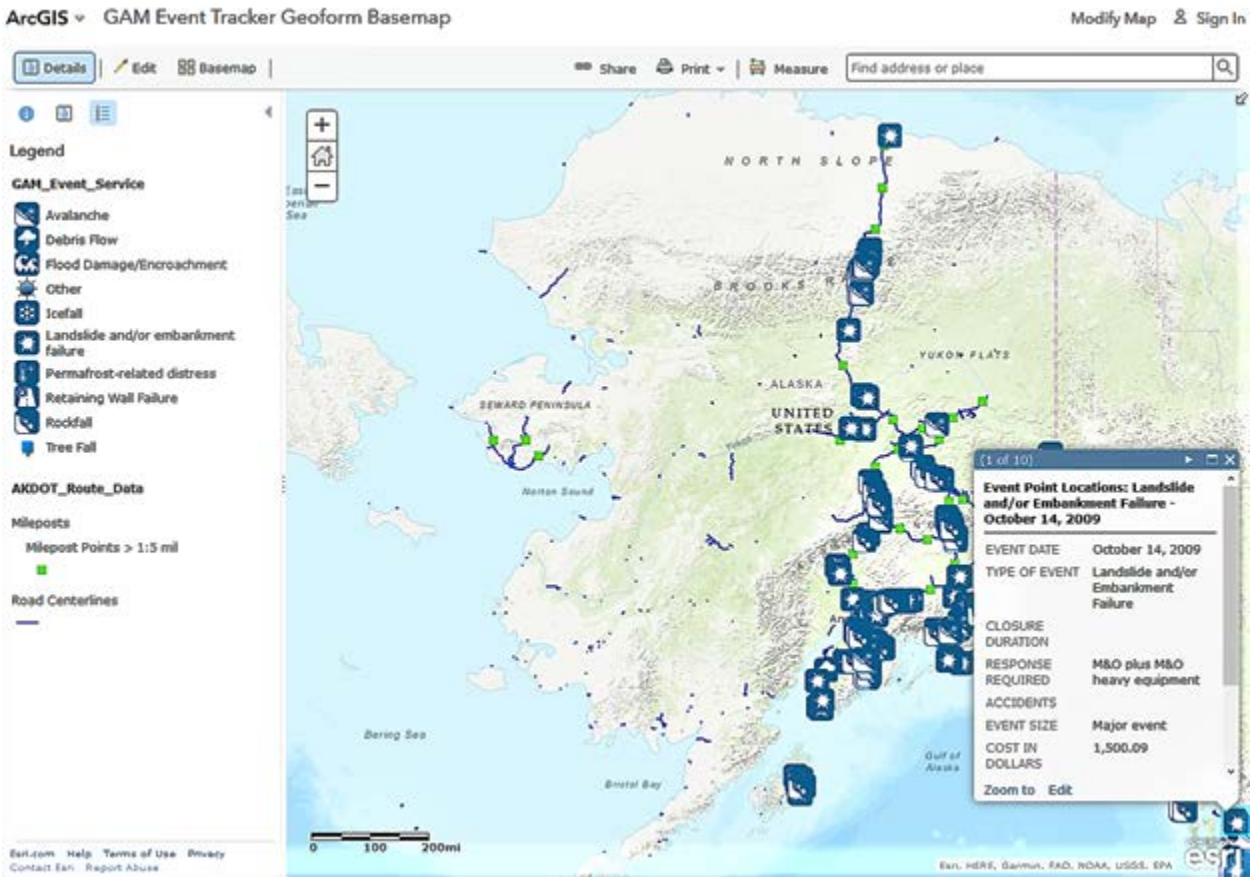

Figure 7-6: Screenshot from the AKDOT&PF Event Tracker website. Symbols show locations of tracked events and event types. Clicking on the symbols brings up additional event information in a popup window like the one shown.

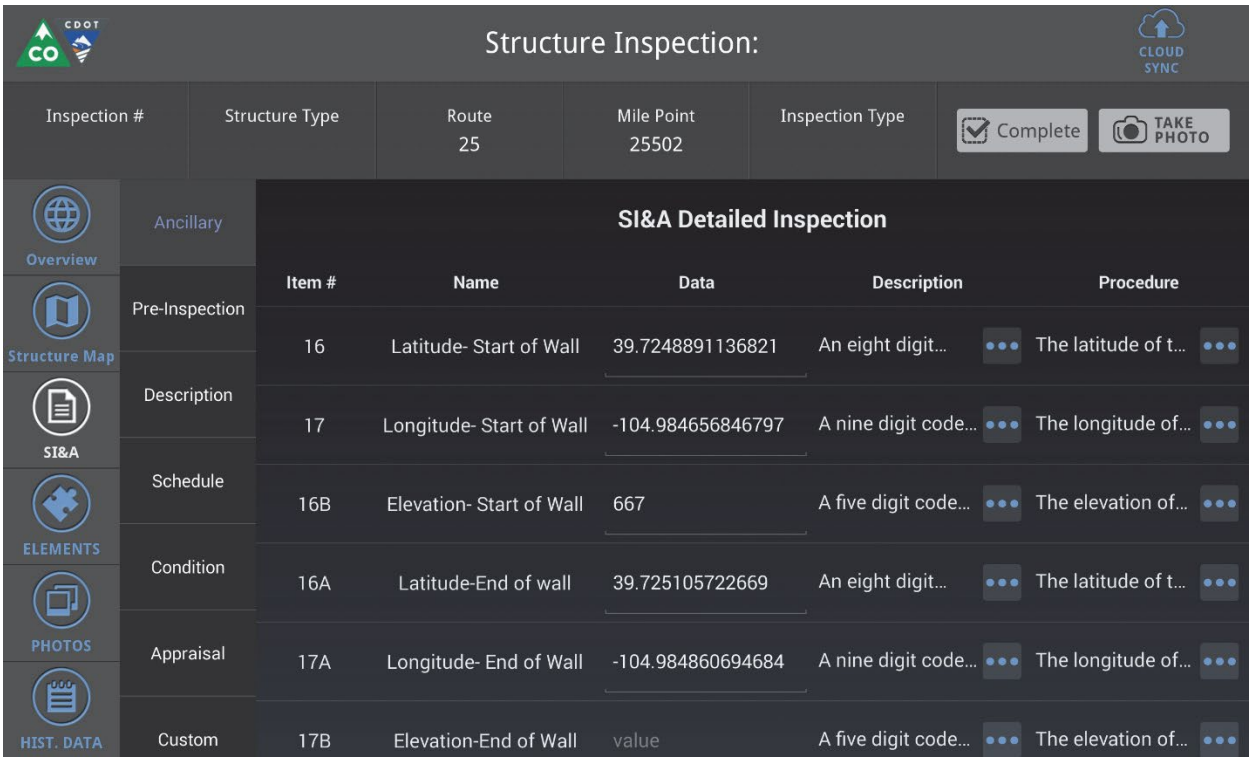

Figure 7-7: Screenshot of mobile application for retaining wall inspection data collection to support CDOT's GAM system.

Source: Vessely et al. 2015.

8 PERFORMANCE MEASUREMENT FOR GEOHAZARD PROGRAMS—EXAMPLE PRACTICES

Measuring the performance of a geohazard program is essential for evaluating the effectiveness of the program, identifying areas for improvement, and aiding in obtaining continual funding for the program. Methods of performance measurement currently used by transportation agencies are described below.

8.1 Colorado Department of Transportation

The geohazards program implemented by CDOT, introduced in Chapter 7, uses a corridor approach to measure performance. Transportation corridors are evaluated for all geohazards that may impact performance. Each corridor is given a grade point average based on risk cost, the total cost associated with the probability and consequence of a geohazard, and calculated from safety, mobility (road user costs), mobility costs associated with each hazard, and the likelihood the hazard will happen. CDOT has made progress in mapping and rating 42 corridors to date. Funding for mitigation is prioritized based on which corridor has the lowest grade point average.

One challenge in assessing the success of mitigation is determining the assumed length of time that it takes for the performance rating of a corridor to be downgraded with no mitigation. This is a major factor in developing performance curves that show how much money could be saved in the long term due to mitigation. Performance curves for the transportation asset can be beneficial in making a case for geohazards program funding, but data are needed to support assumptions made in developing these curves. Instructions for how to address the deterioration of a site and the benefit of specific mitigation measures such as drainage in soft soils or mitigating a rockslide will continue to improve performance measurements. In addition, CDOT has started to incorporate a broader dialogue on risk into design—this is a key focus area of risk.

CDOT is also currently developing a socioeconomic questionnaire to gauge the public's opinion on spending money to perform mitigation measures for geohazards. Once completed, the questionnaire will be released on social media. Public support and involvement can improve the success and performance of a geohazards program.

CDOT completed a study in 2021, "Changing Climate and Extreme Weather Impacts on Geohazards in Colorado," which examined the effect of climate change on the likelihood of geohazards occurring and therefore the performance of affected corridors. (CDOT, 2021)

8.2 Norwegian Geotechnical Institute

Geohazards management performed by the Norwegian Geotechnical Institute (NGI) includes mapping the level of risk due to slope failure. NGI has used reliability methods to calculate the probability of slope failures, not using the factor of safety. Risk is then estimated by considering the number of people affected by a slope failure and the loss of life and money. Risk is mapped across the country by green, red, and yellow risk areas depending on consequences and likelihood of a hazard occurring. Transportation agencies have then used these maps to allocate funding for mitigation. Presenting risk maps that are user-friendly helps to promote geohazards management and communicate the success of a geohazards program to the public.

8.3 Hong Kong Landslip Preventative Measure Program

An example of a geohazards program that has proved successful over time is the government-implemented Landslip Preventative Measure (LPM) program in Hong Kong, China. Hong Kong is a densely populated area with many man-made and natural soil slopes. Landslides in Hong Kong have accounted for more than 470 deaths since 1948, with most failures caused by rain events (Malone 2012). After two major slope failures in the 1970s, the government initiated the LPM program in 1977 to reduce risk from slope failure. The first step the program took was to develop an inventory of all sizable man-made slopes adjacent to developed areas or traffic routes in Hong Kong. The New Slope Catalogue as of 2013 registered 60,000 slopes (Choi and Cheung 2013). Once an inventory of slopes was created, a preliminary study was performed to identify slopes in need of urgent repair. Identified slopes were further examined by using aerial photography, site observations, stability analysis, and occasionally ground investigation to determine if and which mitigation measures were necessary. Upgrades or reconstruction of high-risk slopes were continually performed based on these analyses. The types of mitigation measures implemented to stabilize slopes along roadways included:

- Shotcrete cover at toe of slopes to prevent slopes from moving into the sidewalks and travel roads in busy neighborhoods
- Short masonry retaining walls at the toe of the slope, with pinned geofabric cover on the face of the slope (Choi and Cheung 2013)

Similar combinations are available in the United States, as shown in Figure 8-1.

Figure 8-1: Example of slope stabilization mitigation measures. Anchors and slope face stabilization fabric with topsoil and seeds. Blue Ridge Parkway, Henderson County, NC.

Source: FHWA

Since the LPM program was initiated, approximately 4,500 slopes were repaired or upgraded from 1977 to 2010. The total cost of running the program and implementing repairs was approximately HK$14 billion from 1977 to 2010 (Choi and Cheung 2013). As shown in Figure 8-2, the number of deaths due to landslides in Hong Kong decreased dramatically, despite a 40 percent increase in population, continual hillside developments, and no decrease in rain events (Malone 2012). Landslide risk is currently maintained at a "low as reasonably practicable" level (Choi and Cheung 2013). The LPM program continues to inventory, monitor, and repair slopes. Education and information are also transferred to the public through awareness programs, information services, landslide warning and emergency services, and maintenance campaigns.

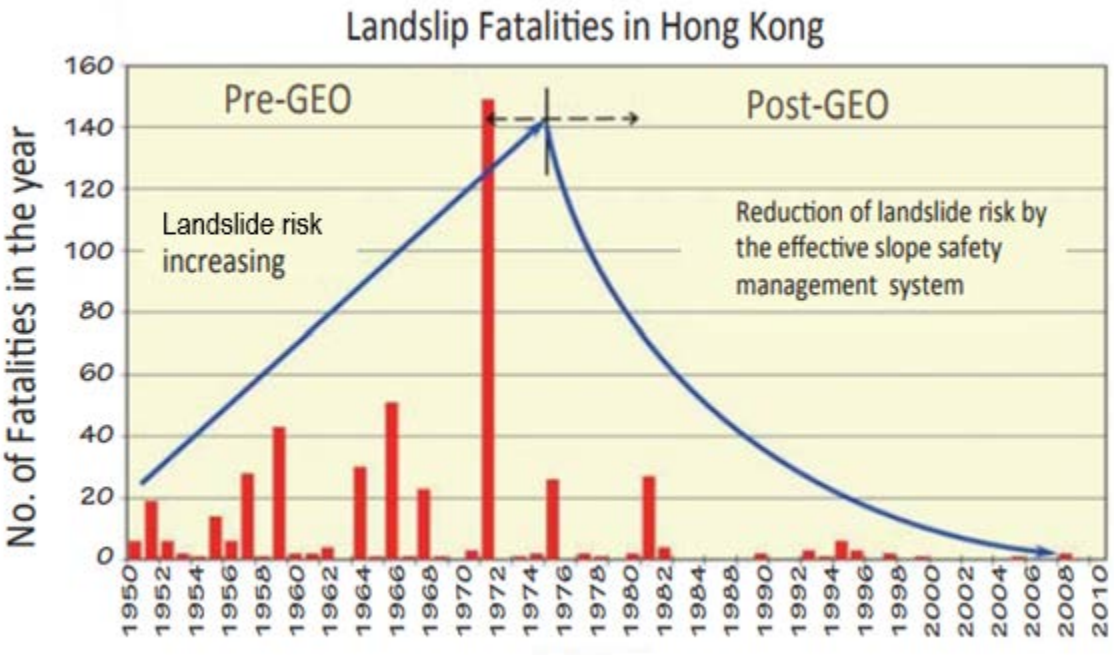

Figure 8-2: Fatalities due to landslides in Hong Kong before and after implementation of a Landslip Preventative Measure program.

Source: Malone 2012.

9 COMMUNICATING TRANSPORTATION GEOHAZARDS

Socioeconomics examines the interaction of economic activity and social processes. Geohazards become problems when they impact society. For instance, when a landslide damages a highway that results in reduced mobility for a community, there are both economic and social impacts to society. When conveying the importance of developing a geohazard management program for a transportation agency, highlighting the socioeconomic benefits is key to connecting with the public and gaining support for the program. Suggestions for including socioeconomic factors in implementation of ADAP for geohazards analyses were discussed in Section 6.2.

Effective communication is especially relevant today, as the FHWA and others aim for greater mindfulness of accessibility and equity for all (FHWA 2021; USDOT 2022). Past Federal transportation investments have too often failed to consider transportation equity for all community members, including traditionally underserved and underrepresented populations (USDOT 2022). Today's transportation professionals should engage with the public in all aspects of geohazard management programs—from planning to maintenance. By doing so they can contribute to advancing transportation "equity for all," including for people of color and "others who have been historically underserved, marginalized, and adversely affected by persistent poverty and inequality" (Executive Order 13985 on Advancing Racial Equity and Support for Underserved Communities Through the Federal Government, January 2021).

State transportation agencies that have developed geohazard management programs have seen the value in communicating the socioeconomic benefits to better serve the public. For instance, CDOT developed a socioeconomic questionnaire, released on social media, to gauge the public's opinion on spending money to perform mitigation measures for geohazards, as discussed in Section 8.1. Minnesota DOT (MnDOT) embarked on a slope vulnerability assessement program to identify, map, and categorize slopes vulnerable to failure with the potential to affect major highways in the State. The program prioritized areas for additional study and proactive stabilization work, and helped better understand and quantify the risk of future slope failures. MnDOT recognized that slope failures can cause millions of dollars in damage and cleanup costs. Slope failures harm or threaten lives and property, have negative environmental impacts, and create lengthy detours resulting in lost economic activity. These socioeconomic consequences drove MnDOT to embark on the slope vulnerability assessment program.

There are also international examples of how risk from geohazards can be communicated to the public. In Norway, as noted in Section 8.2, the Norwegian Geotechnical Institute developed user-friendly maps to identify slope failure risk areas. In Hong Kong, where there is substantial urban development adjacent to hilly terrain, in a climate where torrential rainfall is typical, the Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department of The Government of the Hong Kong Special Administrative Region (CEDD) has been addressing landslide hazards for at least 40 years. GEO was established following landslide disasters at Po Shan Road (a hillside collapse that triggered a landslide that demolished a 12-story residential building and killed 67 people) and Sau Mau Ping (collapse of a 40-meter high road embankment that killed 71 people) in 1972. Details of recent slope stabilization mitigation programs are discussed in Section 8.3. Landslide warning signs have been developed by GEO.

Additionally, GEO developed a series of leaflets and brochures related to landslide prevention, mitigation, and slope safety.

As noted above, there is value in using socioeconomics when communicating transportation geohazards to the public. Potential tools for communication include presentations, workshops, conferences, webinars, websites, and social media. These tools are well developed for other forms of communication. They can be combined with technical expertise of geohazards professionals to create straightforward and clear communication about geohazards to the public. The following process can be applied by transportation agencies:

1. Review examples of how other transportation agencies use socioeconomics for communicating.
2. Identify key socioeconomic concerns relative to geohazards for the transportation agency developing its plan.
3. Develop a communication plan/message that:
    - Addresses these concerns to inform the public about geohazards relevant to the transportation agency.
    - May be used to obtain funds for a geohazards and resilience program.
4. Highlight importance of a geohazards plan to decision-makers.

10 ESTABLISHING GEOHAZARDS MANAGEMENT TECHNIQUES

This chapter provides steps that transportation agencies can take to implement geohazards management techniques and reduce the risks associated with geohazards and extreme events for a transportation system that is resilient to climate change.

10.1 Short-Term Goals

Several actions that can be implemented relatively quickly could help establish a geohazards management program and reduce an agency's exposure to risks associated with geohazards. They include:

- Developing a digital database of geohazard events. Information on the incidence of geohazards is critical for assessing vulnerability and evaluating the likelihood of future events. Including historical events in the database is therefore beneficial. Ideally, the database should include information about event consequences, including agency costs as well as direct and indirect economic consequences. The second step would be to identify and document the type and frequency of geohazards in a State so a geohazards risk management plan could be developed.
- Reaching out to the State geological agency for assistance with geohazard vulnerability identification and assessment. Nearly every State has a geological agency, and geological agency personnel are likely knowledgeable about potential geohazards. Cooperation between the California DOT and the California Geological Survey is an example of the value of geologic agency expertise and knowledge.
- Establishing an agency geohazards task force. Part of the challenge of geohazards management arises from the number of agency groups whose participation is essential. A task force may include:
    - Geologists and geotechnical engineers, and likely other disciplines such as hydraulics engineers, bridge structural engineers, for technical expertise
    - Operations and regional emergency coordinators
    - Transportation planners and engineers, for corridor consequence information
    - Maintenance personnel, for threat-level data
    - Planners, for asset management expertise

  Establishing common goals, clear responsibilities, and open lines of communication among task force members is critical for effective geohazards management.
- Developing information on future/changing environmental conditions that could affect the frequency or intensity of geohazards. This could involve coordinating with climatologists, hydrologists, and environmental staff at environmental and disaster-focused agencies and universities.
- Considering the establishment of a multi-agency geohazards task force, especially in locations where the consequences of geohazards are especially critical. Geohazards typically impact infrastructure beyond simply transportation. Involving other government agencies and private industries could improve prevention and response efforts. Interested stakeholders may include local authorities, power supply and distribution utilities, water

utilities, communication utilities, dam and levee authorities, law enforcement, State Departments of Environmental Protection and/or Natural Resources.
- Developing and applying an ADAP scenarios approach for geohazards, similar to the approach described in Chapter 6.

10.2 Long-Term Goals

Some long-term goals for managing geohazards include:

- Performing a Statewide geohazards vulnerability assessment. Example assessments described in Chapter 5 provide information about the assessments; notably, all assessments involved coordination with external agencies such as State geological agencies.
- Establishing a geohazards training program for field personnel. Field personnel, particularly maintenance personnel, help identify incipient geohazards, collect information about active geohazards, and mitigate consequences. Oregon DOT's training program (Chapter 5) is an example.
- Including the impacts of geohazards in the agency TAM program. Colorado DOT's risk-based program described in Chapter 7 is one approach. Notably, the consequences of geohazards can be included in a TAM program without development of an agency geotechnical asset management (GAM) program, although GAM programs have their own benefits. Geohazards risks can be addressed through independent programs outside of agency TAM systems, e.g., many State landslide and rockfall hazard rating systems. But coordinating the effort with the agency TAM program should result in more efficient decision-making.
- Performing hazard analysis for earthquake and flood hazards using the FEMA Hazus program. The analyses should be based on GIS inventories of the agency's infrastructure (rather than the default national databases). Validation of the analyses using data on past hazard events is also suggested.
- Developing long-term plans for how to keep the data alive in every plan. Plans should be adaptable to future needs and formats, such as GIS platforms and applications.

11 IDENTIFICATION OF GAPS AND RESEARCH NEEDS

The literature review and peer exchange, part of the development for this report, helped identify several gaps in knowledge about geohazards as well as tools available for assessing geohazards. These provide opportunities for further work or research.

For example, a model for **landslides** could be added to the FEMA Hazus program (https://www.fema.gov/flood-maps/products-tools/hazus), in addition to existing models for estimating the risk of damage from earthquakes, floods, hurricanes, and tsunamis.

Road closures are another possible risk assessment topic for further study. Road closures and their consequences are the result of many geohazard events, but procedures for estimating the indirect costs of road closures are not well established. An initial effort should document existing cost estimates for past road closures (e.g., the cost study of rockfall closures in east Tennessee and western North Carolina described in Chapter 5). A concurrent or subsequent effort should focus on methods or tools for estimating the indirect costs associated with road closures. The efforts should include full as well as partial road closures, and closures that are planned as well as emergency road closures. Improving cost estimates for road closures will result in more accurate risk assessments, which should produce more effective management of geohazard risks.

Improving **likelihood estimates** is another avenue for improving geohazard risk management. Ongoing efforts related to data management in transportation generally and geotechnical practices specifically should include management of geohazard information to improve likelihood estimates. A potential research effort could identify the types of information available from geohazard events, and the range of agency practices for collecting and managing the information. The study could include not only major events, but also less significant events that may be captured in agency maintenance logs (e.g., rockfall events that do not impact the roadway).

A related effort might involve using maintenance records to improve likelihood estimates, focusing on the frequency of events and potentially linking the frequency of minor events to that of more significant events (e.g., do minor rockfall events increase in frequency just before a major rockfall?). Likelihood estimates may also be improved by studying links between condition assessment results and geohazards. These links could be studied as part of ongoing or new efforts related to developing procedures for condition assessment. The potential to harness technological improvements for prediction of geohazards should also be considered, for example by using advancements in the movement detection technologies described in Chapter 6 to predict incipient landslides.

Other ideas for further research include:

1. **System-Wide Vulnerability Assessments**
    a. **Lack of data:** Good data are a key component of meaningful vulnerability assessments, but many DOTs lack some basic information on their geotechnical assets. Three important datasets are:
        i. ***Geospatial data showing locations and attributes of slopes*:** Many DOTs do not maintain a detailed inventory of all their slopes in a format that can be used

in GIS. Such data is critical when assessing system-wide vulnerability and for effective asset management. The location of slopes can be determined through desktop GIS analysis of high-resolution elevation data such as is available from aerial LIDAR systems. If such elevation data is not available, then field survey may be used. Attributes of slopes should include the basics like dimensions, slope angle, distance from slope toe to the edge of pavement, the presence/type of stabilization features, presence/type of vegetation, etc. In addition, detailed information on the slope's soils, geology, and hydrogeology should be collected through field assessments to provide the detail needed for accurate assessments (digitized soil and geological maps may not be of sufficient resolution). If available, information on the slope's factor of safety and past/present instability at each slope should also be included and monitored and recorded moving forward.

   ii. ***Geospatial data showing locations and attributes of slope stabilization measures*:** Many DOTs do not maintain a detailed inventory of all their slope stabilization measures (retaining walls, rock nets, etc.) in a geospatial format. The collection/digitization of this data, placing it into a geographic database, and cross-referencing to the slope inventory is important. Basic attribute data for each measure should be included such as dimensions, design features, year installed, condition, etc. Records of failure/repairs should also be included.

   iii. ***High-resolution geospatial data on soils and slopes in the right-of-way*:** As noted above, detailed high-resolution data on soils and geology should be collected for slopes. In some cases, however, more detailed data should be collected beyond steep slopes. This information could be particularly useful in areas with highly expansive soils, karst topography, or permafrost. Having this data should enable a better understanding of the special hazards these areas present and facilitate better planning and maintenance strategies under a changing climate.

b. **Lack of empirical relationships between climate stressors and asset impacts:** Key to system-wide vulnerability assessments is understanding which climate stressor metric is important—and at what level—to determine whether a failure will occur in a geotechnical asset. For example, what rainfall duration and intensity is most important for predicting the failure of a slope? What is the critical threshold of precipitation depth where slope stability could begin to be threatened? The answers to these questions will likely vary across a jurisdiction based on soil types, geology, slope angle, etc. For system-wide assessments of hundreds or thousands of geotechnical assets, this information will likely not be available at a high level of detail or precision. Nonetheless, some effort should be made to understand, based on past experience (either through qualitative observation or more rigorous statistical analysis), the sensitivity of various slopes to climate stressors, and the various mitigating/exacerbating factors. More research and information could identify efficient and accurate ways to understand these relationships across an agency's entire system, at a high level.

2. **Facility-Level Assessments**
    a. **Lack of data:** Just as at the system-wide level, facility-level assessments can be challenged by a lack of detailed soils, geological, and hydrogeological data. Facility-level assessments use more detailed data than system-wide assessments to enable actual engineering analyses of the assets. This is less of a concern for new facilities or planned projects where collection of this information is typically part of routine project fieldwork. The issue is more of a concern for existing assets that do not have any project work planned for them but that were identified as highly vulnerable in the system-wide assessment. For these facilities, field data collection should be part of the facility-level assessment which will make these assessments more time consuming and expensive. As discussed in Chapter 6, a parametric analysis can help screen out some of these analyses to ease the burden, but even parametric analyses involve a basic understanding of the subsurface geology and soils, data that are not always readily available. Furthermore, if the parametric analysis shows the potential for negative impacts, then further data collection should be undertaken. More research and information should be conducted on what types of data to gather to enable various types of facility-level assessments and find the most efficient ways of doing those assessments.
    b. **Lack of understanding on how assets fail:** Facility-level economic analyses of acute climate stressors involve knowledge about how assets fail so that a reasonable climate-stressor damage relationship curve can be developed (see Chapter 6). Under what level of a climate stressor do various impacts start to happen? How do these impacts progress as the severity of the climate stressor increases? Is failure gradual or does it reach a tipping point where it snaps? If there's a tipping point, how is it determined where it lies? This is an area where research is needed s. Having this understanding will also enable better real time monitoring of conditions so that appropriate operations decision can be made to prevent loss and injury during or just prior to extreme weather events.
3. **Incorporating Risk into Planning/Design:** Most, if not all, engineering practices incorporate a determined risk tolerance that is maintained within engineering design standards and methods—determined through statistical analysis of past events. A 100-year storm event is an example of this type of input. This criteria-based approach provides data points, as well as protections from liability for the engineering profession. Yet a risk-based approach should be incorporated that is more robust. The approach should more deeply analyze uncertainties inherent in applied data points—particularly given the large uncertainties within future climate data. Risk-based approaches should include methodologies that allow for a sensitivity assessment for a range of potential stressor values and methods. These can provide a fuller quantification of the value of transportation facilities when considering broader socioeconomic benefits of uninterrupted service.

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