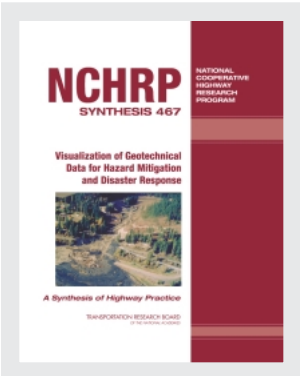

Visualization of Geotechnical Data for Hazard Mitigation and Disaster Response

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 467

Visualization of Geotechnical Data for Hazard Mitigation and Disaster Response

A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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The project that is the subject of this report was a part of the National Cooperative Highway Research Program, conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council.

The members of the technical panel selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

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Cover figure: Bonners Ferry, Idaho. On October 15, 1998, more than 200,000 yards of mud gushed out of North Hill. It covered up a county road, and destroyed a portion of Union Pacific track and a 200 yard area of Highway 95. The mass of mud buried almost one million dollars worth of equipment. Highway 95, Idaho's only major north-south route, was closed three weeks because of the slide. Description: NOAA Nat. Geophysical Data Center.
(*Photo credit*: D. Krammer, Disaster Services Boundary County Idaho.)

ACKNOWLEDGMENTS: The Transportation Research Board would like to thank Lisa Freese, Scott County (MN), Community Services Division, for her review of this report.

FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Jon M. Williams
Program Director
Transportation Research Board

There is a need to understand the use and value of visualization of geotechnical data for mitigating hazards and responding to the consequences of disasters and extreme events. Hazards, disasters, and extreme events with a geotechnical basis include landslides, rockfalls, settlement, sinkholes, and many other events that can degrade or destroy a transportation system. The findings reported in this study provide geotechnical leaders in transportation with an overview of what tools and techniques their colleagues are using and how effective those tools and techniques are for mitigating geotechnical hazards and responding to geotechnical disasters.

Hollie L. Ellis and Mark J. Vessely, Shannon & Wilson, Inc., Seattle, Washington, collected and synthesized the information and wrote the report. Information was gathered by literature review, survey, and interviews. The members of the topic panel that oversaw the study are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

VISUALIZATION OF GEOTECHNICAL DATA FOR HAZARD MITIGATION AND DISASTER RESPONSE

SUMMARY

Visualization of geotechnical data can be an extremely valuable technique for mitigating hazards and responding to the consequences of disasters and extreme events. Geotechnical data visualization (GDV) can be broadly defined as graphic presentation of geotechnical data intended to provide insight into the nature of the problem at hand and to develop potential solutions for that problem. The tools currently used for visualization of geotechnical data include geotechnical-specific applications, applications adapted from other professions, and general-purpose applications such as spreadsheets and image analysis software.

The first objective of this study was to understand the nature and quantity of the geotechnical hazards, disasters, and extreme events that transportation personnel must prepare for and react to. The second objective was to understand what geotechnical data are available to transportation personnel and how the data are stored and visualized. The information gained from the first two approaches provided a context for the third objective: synthesizing the reported effectiveness of data visualization tools in developing and implementing geotechnical hazard mitigation measures and responding to geotechnical disasters or extreme events. The findings reported in this study will provide geotechnical leaders in transportation with an overview of what tools and techniques their colleagues are using and how effective those tools and techniques are for mitigating geotechnical hazards and responding to geotechnical disasters.

Geotechnical data encompasses a varied and complex set of information derived from field reconnaissance, subsurface explorations, field tests, laboratory tests, in-situ instrumentation, and remote sensing measurements. The data may consist of geologic setting, physical properties, or performance characteristics. Geotechnical data range in scale from laboratory tests of small samples to field measurements of mass performance, to wide-area images provided by satellite–borne remote sensing devices. Because these data come from many different sources in many different formats, the greatest challenge to those responsible for hazard mitigation and disaster response is often simply accessing, viewing, and interpreting geotechnical data in a consistent and convenient format.

The natural phenomena that lead to hazards or disasters with a geotechnical component may have geological origins (e.g., earthquakes or volcanoes) or meteorological origins (extreme precipitation or temperature, etc.). Hazards, disasters, and extreme events with a geotechnical basis include landslides, rockfalls, settlement, sinkholes, and many other events that can degrade or destroy a transportation system.

Ideally, every geotechnical hazard associated with a transportation system would be mitigated before a disaster occurs. However, this is not feasible. The economics of mitigating every hazard is unachievable and our ability to recognize, prioritize, and mitigate hazards is imperfect. Consequently, a certain level of risk in building and maintaining transportation systems must be accepted; the most dangerous hazards must be mitigated, and disasters must be responded to as they occur. The role of visualization of geotechnical data is to help reduce those risks by more efficiently identifying hazards and improving mitigation efforts, disaster response, and disaster recovery.

Image credit: U.S.DOT http://www.dot.gov/sites/dot.dev/files/docs/Disaster_National_Transportation_Recovery_Strategy.pdf.

Although the hazards and potential disasters and extreme events may vary from state to state, and even region to region, the effective use of GDV tools and methods in one location can be expected to apply to a range of conditions, events, and objectives in another location. A goal of this study was to identify the GDV approaches that are most effective for hazard mitigation and disaster response and recovery.

Mitigation and response to geotechnical disasters or extreme events are part of the transportation emergency management cycle. Mitigation of a geotechnical hazard occurs during the preparation phase, with an objective of avoiding or minimizing hazards and reducing disaster consequences. During the response phase, immediately following a disaster, the focus is on public and worker safety and minimizing transportation system delays or detours. Mitigation also occurs during the recovery phase of restoring the transportation system to a pre-event level of service. Recovery mitigation is also an opportunity to make improvements to aging infrastructure by rebuilding a more resilient transportation system than existed previously.

The primary sources of information for the study were a literature review; a survey of U.S. state department of transportation (DOT) geotechnical leaders; and interviews with selected railroad and pipeline geotechnical personnel, visualization research leaders in academia, and GDV software vendors.

The literature review was used to obtain an overview of the research and development (R&D) underway in the field of GDV and to sample the case histories that illustrate the value and limitations of GDV in practice. An exhaustive list of all publications from as few as the last 10 years would likely run to thousands of citations. Consequently, the bibliography attached to this report is only a small sampling of the more recent publications. Considering the current and likely continuing rapid pace of technological change, preference in building the bibliography was given to more recent publications.

The publications found in the literature review represent a broad spectrum of GDV purposes, technologies, and methods. Although the publications that describe case histories or new methods are usually for a specific transportation system type (e.g., road, rail, or pipeline), the lessons learned and methods described are generally applicable to any transportation system.

It is interesting to note that in the literature there are a number of introspective studies of the impact of visualization technology on the productivity, quality, and mission support in the sciences and engineering. The conclusion of these studies is that, despite cost and implementation challenges, visualization technology has improved the pace, quality, and depth of understanding in the fields where it has been applied.

A survey of state DOT geotechnical leaders was undertaken to determine the type and quantity of natural phenomena and geotechnical hazards that they face, what geotechnical data they collect, store and use, and what tools they have at their disposal to visualize geotechnical data; and to gauge the frequency and effectiveness of their use of visualization in mitigating geotechnical hazards and responding and recovering from geotechnical disasters and extreme events. The survey was sent to the geotechnical leaders of the 50 states, the District of Columbia, and Puerto Rico. Responses were received from 41 states and Puerto Rico, a response rate of 81%.

On average, state DOT geotechnical leaders and their staffs face five different natural hazards and seven geotechnical hazards, with some states having as many as eight natural phenomena hazards and 12 geotechnical hazards to contend with. Although natural hazards with a geological origin such as earthquakes were reported by many states, the majority of the natural phenomena hazards the states face are meteorological.

To identify and mitigate this array of hazards, the state DOTs collect, store, and use a wide range of geotechnical information including exploration and test data, instrumentation data, and remote sensing data. The typical DOT maintains about eight different types of geotechnical data and six different types of instrumentation data. Some DOTs maintain as many as 14 geotechnical data types and some have as many as 13 instrument data types to manage. Geotechnical data management practices among DOTs range from manual data collection and paper files to the latest instrument data acquisition systems and sophisticated, centralized information management systems.

The general consensus among the state DOT geotechnical leaders is that visualization of geotechnical data is valuable for hazard mitigation and disaster response. However, many of the DOTs noted that a significant gap exists between the desired level of data availability and visualization tools and their current ability to achieve that level.

Interviews with geotechnical leaders in other transportation system arenas (rail and pipeline), indicated that they are faced with similar geotechnical hazards, disasters, and extreme events. However, because they represent for-profit organizations, they can more aggressively integrate visualization tools and other technologies into their decision-making processes than may be possible at the state agencies, where a multitude of goals compete for finite funding.

The R&D underway in the academic world bodes well for the improvement and widespread use of visualization of geotechnical data; not just for hazard mitigation and disaster response, but for geotechnical engineering in general. Much of the R&D is focused on software, hardware, and data management, but development of improved human-machine interaction may prove to be the most valuable outcome of this research.

Key findings of the literature review, survey, and interviews may be summarized as follows:

- The natural phenomena hazards that threaten transportation systems throughout the United States include hazards of geological origin, but are dominated by meteorological hazards.
- Almost every type of geotechnical hazard threatens transportation systems, but the most common are unstable rock or soil slopes and embankments, settlement issues, and sinkholes.
- The most costly hazards are unstable rock or soil slopes and embankments.
- Traditional geotechnical, instrument, and remote sensing data are collected and retained, but some DOTs have yet to implement systems to readily access and visualize the data.
- Most DOTs report that geotechnical hazard mitigation is generally successful and that visualization of geotechnical data has an important role in identifying hazards and implementing mitigation measures.
- Most geotechnical leaders would like to have a substantial amount of geotechnical data available online and on site during geotechnical disaster response, but relatively few have the facilities to accomplish this goal.
- When available, GDV plays an important role in responding to geotechnical disasters.
- Visualization of geotechnical data also has an important role in long-term recovery from geotechnical disasters.

CHAPTER ONE

INTRODUCTION

WHAT IS GEOTECHNICAL DATA VISUALIZATION?

Although there are a wide variety of potential visualization approaches and tools, geotechnical data visualization (GDV) for hazard mitigation and disaster response and recovery can be very broadly defined as graphic presentation of geotechnical data in an attempt to gain insight into the nature of the problem at hand, and that which can then be used to develop potential solutions for that problem. The graphic presentation could range from a simple X-Y plot to an interactive, three-dimensional view of subsurface conditions in a transportation corridor.

The diagram in Figure 1 illustrates the factors—user, situation, objective, data, and tools—that generally influence what, how, and when GDV is used. Clearly, there will not be one GDV solution for every case: Each user may have different skills, tools, and goals; and each situation will have unique conditions and timing. The objectives and the type and extent of the available data will vary from case to case. While the factors shown in Figure 1 may lead to widely different GDV approaches for different situations, their common thread and significant characteristic is a transformation from data to understanding.

Another definition applicable to visualization of geotechnical data for hazard mitigation and disaster recovery is found in the Federal Lands Highway Division's Design Visualization Guide (http://www.efl.fhwa.dot.gov/manuals/dv) and shown at the bottom of column one While this guide focuses on the visualization of design concepts in the context of answering the question "How will the project look when it is done?", the tools and techniques presented in the guide could be adopted and adapted to visualization of geotechnical data for hazard mitigation and disaster recovery.

Design visualization could be defined at its simplest as the simulated representation of a design concept and its contextual impacts or improvements. Traditionally, design visualization (DV) techniques have been directed towards better communication of what the design will look like. This focus has driven a broad application of DV in the public involvement area: Visualization is almost always a required component of large-scale infrastructure and transportation projects. More recently, the focus has been the integration of DV into the overall notion of "context sensitive" design.

The Design Visualization Guide presents a range of routine and innovative visualization tools and techniques including image acquisition, photograph manipulation, interactive and animated two- and three-dimensional applications, stereoscopic imaging, analytic simulation, and schedule- or event-driven four-dimensional visualizations (space and time).

STUDY METHODOLOGY

The methods used to gather the information for this study consisted of the following:

- A questionnaire submitted to the geotechnical leaders at the 50 U.S. state Departments of Transportation (DOTs) and others
- Literature search, review, and synthesis
- Interviews with geotechnical leaders at several rail and pipeline transportation agencies or companies
- Interviews with several GDV leaders in academia
- Interviews with GDV software vendors.

Study Questionnaire

The purpose of the study questionnaire was to

- Determine the nature of geotechnical hazards and disasters faced by the state DOTs and others in the transportation sector
- Understand their data management and processing environment
- Ascertain how they use GDV tools and techniques to
  - develop and implement geotechnical hazard mitigation measures
  - respond to geotechnical disasters and extreme events
- Obtain their opinion about the use and value of GDV tools and techniques.

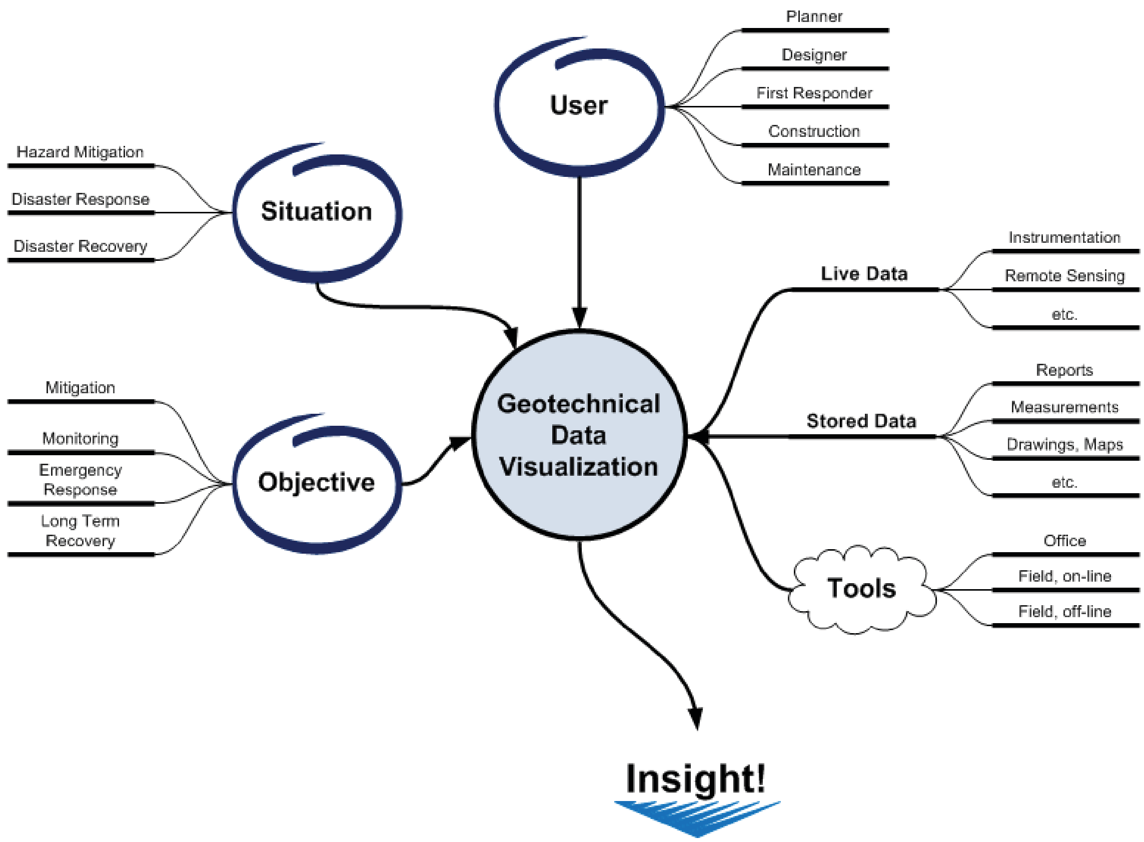

FIGURE 1 The factors—user, situation, objective, data, and tools—that generally influence what, how, and when GDV is used.

The questionnaire, included in Appendix A, consisted of 37 primarily closed-end questions organized in the following six sections:

1. Hazards, Disasters, and Extreme Events
2. Geotechnical Data Management
3. Hazard Mitigation to Avert Disaster
4. Responding to Disasters and Extreme Events
5. Long-Term Recovery from Disasters and Extreme Events
6. Evaluation and Opinion.

Section 1 addressed the types of natural phenomena, geotechnical hazards, and geotechnical disasters encountered by the DOTs. The natural phenomena in a region (geological and meteorological) generally determine the types of geotechnical hazards and disasters that may occur. An identical list of geotechnical hazards and geotechnical disasters was provided in this section under the presumption that any geotechnical hazard, if not mitigated, could become a geotechnical disaster.

Section 2 was used to assess how the DOTs collect, process, store, and use geotechnical data when developing and implementing hazard mitigation measures or when responding to disaster or extreme events. The general categories of the questions in this section were:

- Geotechnical data collection, storage, and retention
- Geotechnical instrumentation usage and processing
- Geotechnical remote sensing usage and sources
- GDV software usage and users.

Section 3 was used to determine the types of hazards the DOTs have attempted to mitigate, and how and when they have used GDV in these efforts. Respondents were asked to identify successful and unsuccessful mitigation efforts. They were also asked to identify how and when GDV is used in a mitigation project and how visualization affected the outcome of their mitigation projects.

Section 4 was used to assess how the DOTs use GDV when responding to disasters. These questions focused on the use of geotechnical data in the emergency response immediately following the occurrence of a disaster.

Section 5 was used to assess how the DOTs use GDV to facilitate long-term disaster recovery. Respondents were asked to identify the most useful geotechnical data for long-term recovery and to specify how visualization of the data helped achieve recovery.

The questions in Section 6 addressed the frequency and level of use of GDV by the DOTs and were used to gauge their opinion on the utility and value of GDV in hazard mitigation and disaster response.

Responses to the survey questions are summarized in matrix form in Appendix B and commentary by the study authors is presented in Appendix C.

Literature Review

The literature review consisted of a search for national and international journal articles, conference proceedings, reference works, academic research, thesis publications, and textbooks related to the collection, storage, processing, and visualization of geotechnical data. The search was not limited to uses specific to geotechnical hazard mitigation or disaster and extreme event response, as it can be expected that some GDV tools and methods that have been found to be effective in general geotechnical practice would also be effective in such cases. Because of the large number of references found in the literature search, the search results were filtered to remove references less applicable to the study objectives. The search results were further filtered by removing references that were more than about 10 years old and referred to outdated technologies.

Interviews

Geotechnical leaders at several railroad and pipeline companies were interviewed in order to evaluate the similarities and differences to the state DOTs' approach to geotechnical hazard mitigation and disaster response, and to gauge their companies' use of GDV. Interviews were conducted with Frank Wuttig of Alyeska Pipeline Company, Lewis Ruder of the Burlington Northern–Santa Fe Corporation, and Dr. Caleb Douglas of the Union Pacific Corporation.

Interviews with academic R&D leaders were conducted to gain an understanding of the potential future of GDV. These interviews were directed to researchers who are focusing on visualization of natural phenomena and geotechnical hazards and who are exploring the challenges of transferring research and new technologies to geotechnical practice. Interviews were completed with Dr. Michael Olsen at Oregon State University, Dr. Tony Szwilski at Marshall University, and Dr. Gregory Jones at the Scientific Computing and Imaging Institute of the University of Utah.

Several developers and vendors of GDV software were also interviewed to examine how their industry participates in the transfer of visualization technology from research to practice. The software vendors were also requested to provide examples images from their GDV software.

CHAPTER TWO

HAZARDS, DISASTERS, AND EXTREME EVENTS

DEFINITIONS

The following definitions were provided in the preamble to the questionnaire sent to the state DOT geotechnical leaders:

- Hazard: Condition or situation with the potential to cause harm.
- Disaster: Outcome of a hazard when it changes from potential event to actual event.
- Geotechnical Data Visualization: Viewing and/or analyzing geotechnical data using visual software.

The following additional definitions are provided to clarify terms used in this report:

- Natural phenomena hazard: A natural condition or extreme event that may threaten a transportation system.
- Geotechnical hazard: A threat attributable to the soil, rock, and/or groundwater beneath or adjacent to a transportation system.
- Geotechnical hazard mitigation: Identification, monitoring, design, and construction of mitigation measures for a geotechnical hazard.
- Geotechnical disaster response: Immediate and short-term response to a geotechnical event to assist in rescue efforts, protect public and worker safety, and reduce transportation system delays or detours.
- Geotechnical disaster recovery: Long-term recovery from a geotechnical event to restore public safety and transportation system functionality.

Several systems of classifying natural phenomena hazards have been proposed. For example, the Organization of America States (OAS) has proposed the classification system shown in Table 1 (http://www.oas.org/dsd/publications/Unit/oea54e/ch05.htm) and the Centre for Research on the Epidemiology of Disasters (CRED) in Europe has proposed the system shown in Table 2 (http://www.emdat.be/classification). Although each of these systems has its purposes and advantages, for report purposes it is simpler to classify natural phenomena hazard origins as geological or meteorological (including climatologic and hydrologic sources) because geotechnical hazards may arise from multiple natural phenomena hazards: For example, an unstable slope may arise from seismic activity (geological origin) or extreme precipitation (meteorological origin). The survey of state DOT geotechnical leaders indicates that as many as 90% of the geotechnical disasters they have encountered are the result of meteorological events.

Geotechnical hazards can be naturally occurring conditions (e.g., unstable slopes or soft soils) or can arise from the constructed features of a transportation system (embankment fills or cut slopes, etc.). The most commonly encountered geotechnical hazards are summarized in Table 3. This table also identifies the potential origin(s) of the geotechnical hazard.

Although the hazards may vary from state to state, and even region to region within a state, the effective use of GDV tools and methods in one location can be expected to apply to a range of conditions, events, and objectives in another location.

The following are several examples of natural phenomena that have led to geotechnical disasters and damage to transportation systems.

EXAMPLES OF NATURAL PHENOMENA

Landslide, Oso, Washington, March 2014

The landslide disaster of March 22, 2014 near Oso, Washington (Figure 2), cost more than 40 lives, temporarily dammed the Stillaguamish River, and blocked Washington State Route 530. The landslide occurred after a period of unusually intense rainfall, but the specific causes of the landslide are still under investigation. A U.S. Geological Survey (USGS) website (http://www.usgs.gov/blogs/features/usgs_top_story/landslide-in-washington-state/) has several other examples of GDV for this disaster. In addition to a lidar (light detection and ranging) image similar to the one shown in Figure 2, the website has a video of a landslide runout model and seismograph records used to confirm that the landslide was not caused by an earthquake. While use of high resolution lidar images and other visualization techniques would not change the need to route a highway through this valley, the newer images will likely improve the understanding and perception of risk to lives and infrastructure.

Rockfall, Thermopolis, Wyoming, 2002

The rockfall on a railway embankment shown in Figure 3 occurred after spring runoff eroded the soil underlying a tufa formation. Note the ties and rails in the right-center of the

TABLE 1
HAZARD CLASSIFICATION SYSTEM (OAS)

Category	Hazard Examples
Atmospheric	Hailstorms, hurricanes, lightning, tornadoes, tropical storms
Seismic	Fault ruptures, ground shaking, landslides, lateral spreading, liquefaction, tsunamis, seiches
Other Geologic or Hydrologic	Debris avalanches, expansive soils, landslides, rockfalls, submarine slides, subsidence
Hydrologic	Coastal flooding, desertification, salinization, drought, erosion and sedimentation, river flooding, storm surges
Volcanic	Tephra (ash, cinders, lapilli), gases, lava flows, mudflows, projectiles and lateral blasts, pyroclastic flows
Wildfire	Brush, forest, grass, savannah

TABLE 2
HAZARD CLASSIFICATION SYSTEM (CRED)

Hazard Subgroup	Definition	Hazard Main Type
Geophysical	Events originating from solid earth	Earthquake, volcano, mass movement (dry)
Meteorological	Events caused by short-lived, small to meso-scale atmospheric processes (in the spectrum from minutes to days)	Storm
Hydrological	Events caused by deviations in the normal water cycle or overflow of bodies of water caused by wind set-up	Flood, mass movement (wet)
Climatological	Events caused by long-lived, meso- to macro-scale processes (in the spectrum from intra-seasonal to multi-decadal climate variability)	Extreme temperature, drought, wildfire

TABLE 3
GEOTECHNICAL HAZARDS

	Hazard Origin		
	Natural phenomena		
Hazard	Geological[1]	Meteorological[2]	Human action
Slopes (natural or cut)	x	x	x
Embankments		x	x
Slope Creep	x	x	x
Rockfalls	x	x	x
Avalanches	x	x	x
Debris Flows	x	x	x
Settlement or Heave	x	x	x
Sinkholes	x	x	x
Subsidence	x	x	x
Lateral Spreading	x		
Liquefaction	x		
Surface Ruptures	x		
Frost Heave		x	
Permafrost Thaw/Freeze		x	
Frozen Debris Lobes	x	x	
Tsunamis	x		
Seiches	x	x	
Storm Surge		x	
Wind Blown Soil/Dunes		x	x

[1]Earthquakes, volcanoes.
[2]Includes hydrological and climatological phenomena.

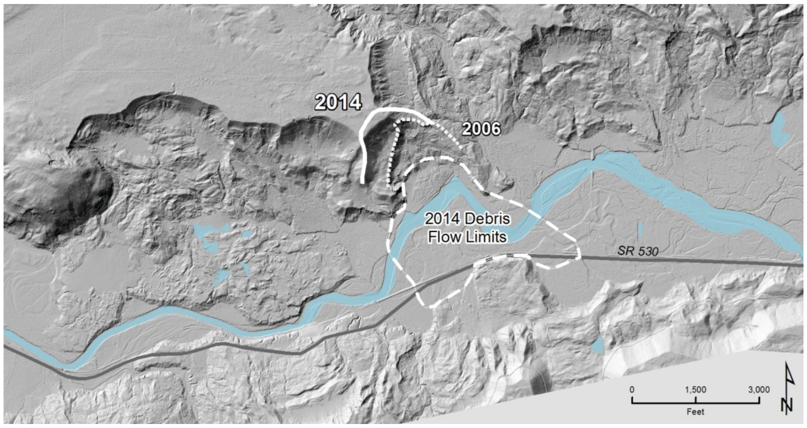

FIGURE 2 Landslide, Oso, Washington, March 2014. (*Image credit*: Puget Sound Lidar Consortium, 2013.)

photograph that were pushed off the embankment by the rockfall. A better understanding of the local geology and seasonal groundwater conditions might have led to hazard mitigation measures that could have avoided this disaster.

Earthquake Sand Boils, Seattle, Washington, February 2001

Among the many consequences of the February 28, 2001, earthquake centered near Nisqually, Washington, was the appearance of sand boils on King County International Airport (aka Boeing Field) taxiways and runways. Liquefied sand was ejected through pavement joints and cracks opened by the 6.8 (moment magnitude scale) earthquake as shown in Figure 4. The sand boils occurred in limited areas on the taxiway, runway, and in adjacent grass-covered areas, indicating that liquefiable soils in the airport subgrade may be isolated. The airport is built on a former river floodplain, which may have buried channels of liquefiable soils that led to the limited sand boil area. Although the airport area is almost entirely paved, air photographs from areas upstream of the airport indicate the presence of buried former river channels.

FIGURE 3 Rockfall, Thermopolis, Wyoming, 2002. (*Photo credit*: D. McCulloch.)

Debris Flows, Beartooth Highway, Montana, May 2005

A spring rain-on-snow event in the Beartooth Mountains of eastern Montana resulted in massive debris flows that damaged 13 locations on the steep hairpin highway leading to an eastern entrance to Yellowstone Park. Figure 5 shows two of the damage locations (note the damage to the upper switchback near the top of the photograph).

Because this highway provides access to the park and is critical to local economy, a design-build team was awarded a contract to restore the highway in a single construction season rather than using a traditional design-bid-build contract that might have taken more than two years to complete.

GDV tools played a critical role in rapid assessment, design, and construction of the repairs. The primary visualization tools were air photography and the visualization features of the stability and retaining wall design tools used by the team. Design and construction was a dynamic process:

FIGURE 4 Nisqually Earthquake, February 2001, sand boils, Boeing Field Taxiway, Seattle, Washington. (*Photo credit*: M. Anderson.)

FIGURE 5 Debris flow, May 2005, Beartooth Highway, Montana. (*Photo credit*: Montana Department of Transportation.)

FIGURE 6 Landslide, October 1998, Bonner's Ferry, Idaho. (*Photo credit*: D. Krammer, Disaster Services, Boundary County, Idaho.)

Concepts were developed, designs advanced, equipment mobilized, and materials ordered as explorations, excavations, and construction were in progress. Repairs were completed in four months at an estimated savings of $6 million.

Landslide and Debris Flow, Bonners Ferry, Idaho, October 1998

The following description of the geotechnical disaster that damaged two roads and a railroad is from the National Oceanic and Atmospheric Administration's National Geophysical Data Center (http://www.ngdc.noaa.gov/hazardimages):

> On October 15, 1998, more than 200,000 [cubic yards] of mud gushed out of North Hill. It covered up a county road, and destroyed a portion of Union Pacific track and a 200-yard area of Highway 95. The mass of mud buried almost one million dollars worth of equipment. Note the rails still suspended in air after the collapse of material beneath them. Highway 95, Idaho's only major north-south route, was closed [for] three weeks because of the slide.

The buried equipment was being used to cut into the toe of slope. The cut exposed saturated, soft and loose, prehistoric glacial lake sediments which are seen in the debris runout in the lower part of the photograph in Figure 6.

CHAPTER THREE

GEOTECHNICAL DATA TYPES AND SOURCES

The greatest challenge to those responsible for hazard mitigation and disaster response is often simply accessing, viewing, and interpreting geotechnical data in a consistent and convenient format. The following sections provide an overview of geotechnical data sources and the methods used to store and access the data.

RECONNAISSANCE, EXPLORATION, AND TESTING

The variety and complexity of geotechnical data obtained by field reconnaissance, exploration, and field and laboratory testing can be demonstrated by a review of any of several guidance documents for geotechnical investigations. For example, the *Manual on Subsurface Investigations* (AASHTO 1988) lists more than 20 general subsurface data requirements concerning stratum boundaries, groundwater, foundation support, slope stability, seismicity, material properties, and so on. These data requirements are applicable to roadways, air fields, rail and transit track beds, tunnels, culverts and pipes, cuts and fills, and associated transportation structures.

The AASHTO manual also includes guidance for conducting, compiling, and presenting geotechnical data from field reconnaissance, engineering geophysics, subsurface exploration, in situ testing, hydrogeologic investigation, and laboratory testing of soil and rock.

INSTRUMENTATION

Instrumentation is a general term for sensors and data acquisition devices used to measure temporal changes in soil, rock, groundwater, and structures. Instrumentation is distinguished from remote sensing (see next section) in that the sensor is installed in or on the ground or structure; whereas remote sensing devices provide measurements without being in contact with or modifying the measured object.

Geotechnical instrumentation includes piezometers, slope movement devices, displacement and strain gages, extensometers, pressure cells, thermistors, and other sensors that are used to repeatedly measure the condition of the soil, rock, groundwater, or structure at a specific location and time. These instruments are generally precise, accurate, and robust; and can be left unattended and monitored remotely. Instrumentation automation is essential for rapid visualization of geotechnical measurements. Most geotechnical instrumentation has the disadvantage of providing point measurements in situations that may require more comprehensive measurements; and, in some instances, the installation of the instrument can alter the original condition of the soil, rock, groundwater, or structure being measured.

REMOTE SENSING DEVICES

As noted, remote sensors are a special class of instruments that acquire information without being in contact with or modifying the object or area being measured. Some of the remote sensing technologies that are commonly used to acquire geotechnical and geophysical data are shown in Figure 7. Remote sensing devices are generally classified as passive or active, depending on whether they rely on reflected wave energy or emit and receive wave energy from the object being measured.

GEOPHYSICAL DEVICES

Remote sensors for geophysical applications are a separate group of devices used to measure gravitational, magnetic, electrical, or seismic properties of the subsurface. The devices generally require a driving force, and the ground response to the driving force is measured by passive sensors. The devices provide a relative measure of subsurface properties which can be used to infer such features as differing soil unit thickness, location of soft zones or voids, or groundwater depth.

Remote sensing devices can be airborne (aircraft or satellite) or ground-based. Many remote sensors can only acquire ground surface data, but geophysical remote sensing devices can provide images of subsurface conditions. A comprehensive review of spaceborne and airborne remote sensing for geotechnical applications is provided in Rathje et al. (2006).

Although the precision and accuracy of remote sensors vary widely, some devices can provide sub-millimeter accuracy. Specialized software and personnel are generally required to process raw remotely sensed data, but processed remote

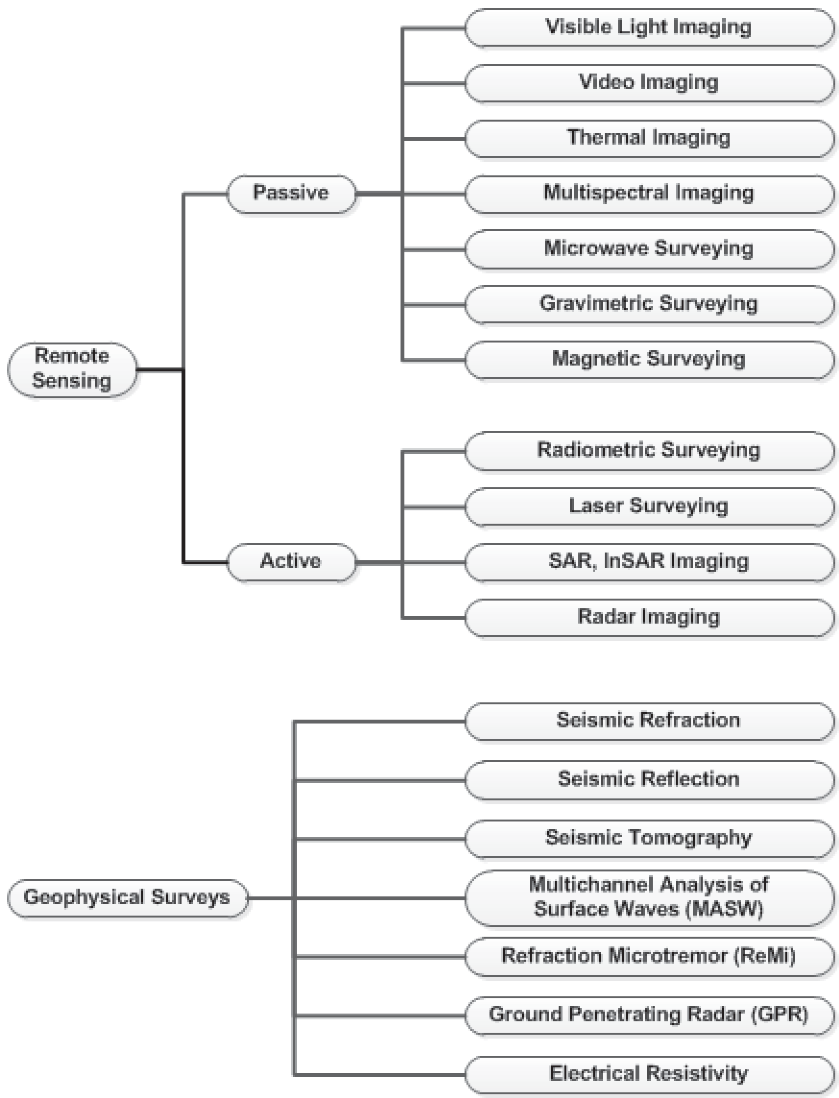

FIGURE 7 Remote sensing and geophysics for geotechnical applications.

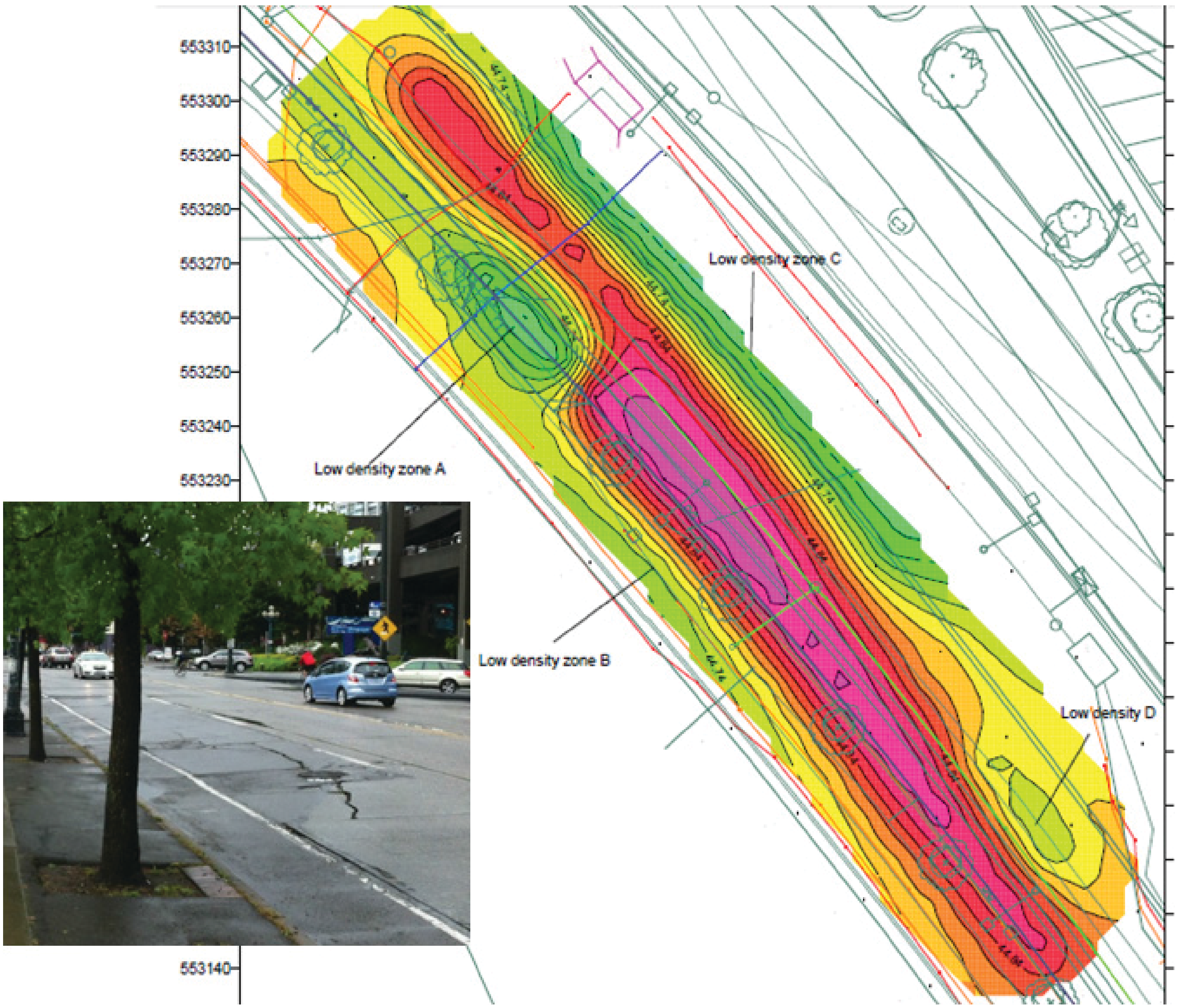

FIGURE 8 Bouguer microgravity survey of low density subgrade. (*Contour plot credit*: Parsons Transportation Group.) (*Photograph credit*: P. Van Horne.)

sensing images and surveys are available from several public and commercial sources.

An example of a remote sensing method is shown in Figure 8. The colored contours in the plan view are the results of a Bouguer microgravity survey (gravimetric survey) to determine the extent of potential voids or low density subgrade beneath a roadway pavement. The green and yellow contours indicate locations of potential voids or low density subgrade. The distressed pavement in the curbside lane of the roadway shown in the photograph is identified as "Low density zone A" in the plan view.

CHAPTER FOUR

LITERATURE REVIEW

Approximately 200 national and international journal articles, conference presentations, academic research reports, and thesis publications related to the collection, storage, processing, and visualization of geotechnical data are provided in the bibliography of this study report. The bibliography was developed from focused searches of British Library Inside Conferences, Civil Engineering Abstracts, Earthquake Engineering Abstracts, EI Compendex, GEOBASE, GeoRef, National Technical Information Service, ProQuest Dissertations and Theses, Transport Research International Documentation (TRID), and the web. The searches used key words related to visualization of geotechnical data without restricting the search results to specific reference to geotechnical hazard mitigation or disaster response. The search results were filtered visually to remove any off-topic results.

The distribution of the sources of the bibliography entries is shown in Figure 9. Although the sampling procedure for the bibliography was not random, more than 40% of the entries are from dissertations, which is likely a reflection of the level of interest in GDV in academia.

The distribution of the major topics of the bibliographic entries is shown in Figure 10. The major topic categories were defined as:

- Hazards: Identification, classification, mitigation, or visualization of natural phenomena and geotechnical hazards.
- Instruments: Use of geotechnical instruments or instrumentation software for hazard monitoring.
- Remote sensing and geophysics: Use of remotely sensed data or remote sensing software for geotechnical hazard or disaster monitoring.
- Geographic Information System (GIS): Use or development of geospatial techniques for geotechnical hazard or disaster monitoring and evaluation.
- Risk: Application of risk assessment or risk analysis methods to geotechnical hazard mitigation or disaster response.
- Data management: Use or development of data management methods to organize and visualize geotechnical data.
- Modeling: Use or development of numerical or physical models to evaluate geotechnical hazards.
- Technology: General discussion of the state and future of GDV techniques and software.

Many of the entries could fall in two or more categories. For example, several of the entries categorized as “remote sensing” also address incorporating the remotely sensed data into a GIS application.

The major takeaways from the literature review are: one, the breadth and depth of the technologies and methods being developed and used for visualization of geotechnical data; and two, the pace at which this technology changes. The new developments and applications will improve geotechnical engineering professionals’ ability to visualize and solve geotechnical hazard mitigation and disaster response issues; but it will also challenge them to keep abreast of and adopt the new technologies.

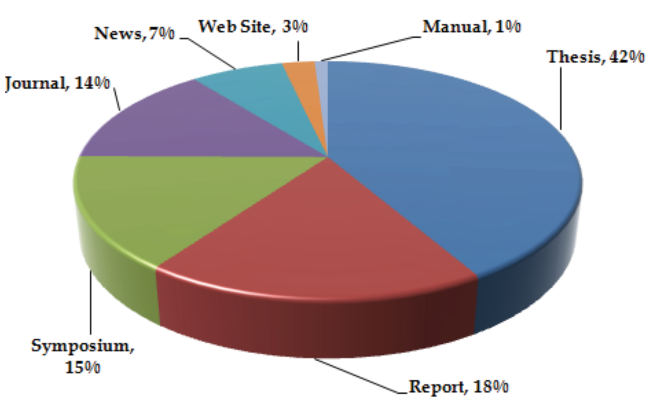

FIGURE 9 Bibliography source distribution.

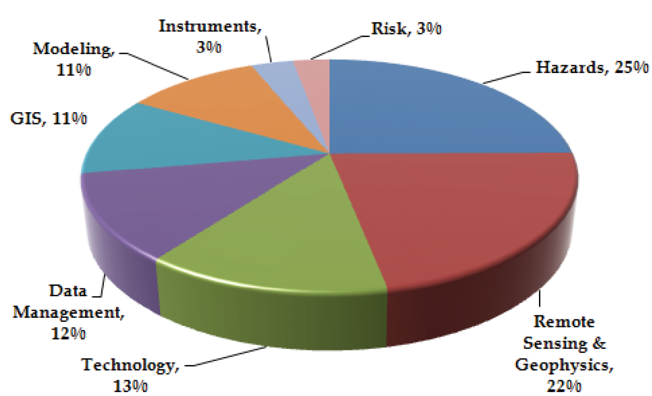

FIGURE 10 Bibliography subject distribution.

CHAPTER FIVE

CURRENT GEOTECHNICAL VISUALIZATION TECHNOLOGY

The data visualization tools available to the practicing geotechnical engineer range from simple x-y graphing programs to sophisticated software systems that integrate multiple graphics tools with complex databases and data and image acquisition software. Visualization software is available in proprietary and open-source formats. Open-source software is developed and supported by an online community of developers and users and is generally free to the end user. Most of the GDV tools available today are desktop software programs; but online, cloud-based tools are becoming more available.

Geotechnical engineers have the multiple challenges of identifying which visualization tools to apply in any situation (e.g., hazard mitigation, disaster response); knowing how to effectively apply the tools; and keeping abreast of new technology. The following sections provide an overview of the available types and variety of GDV software.

Although this study report is focused on visualization of geotechnical data for hazard mitigation and disaster response, the visualization tools discussed in this report are equally applicable to transportation system activities such as planning, design, construction, and maintenance. The number of different software programs cited in the following sections was determined from a search of the geotechnical literature and Internet for geotechnical software vendors, open source organizations, and online software providers (see Figure 11). The software titles identified in the search are listed in Appendix D. Inclusion of a software title in these lists does not imply an endorsement of the product by the National Academies of Science or the TRB. There may be other software programs not identified by this search that are being used by geotechnical professionals.

SPREADSHEET SOFTWARE

There are about three dozen different proprietary desktop spreadsheet programs; at least seven proprietary online spreadsheet programs; and a dozen or so open-source spreadsheet programs available. Despite this variety, every geotechnical leader at the DOTs and railroad and pipeline companies reported that they and their staff use the same desktop program. The advantages of using a common spreadsheet program include ease of sharing data and methods.

The most common use of spreadsheet programs for visualization of geotechnical data is to generate x-y graphs to explore and illustrate data relationships. Most spreadsheet programs also have the capability to generate pie, bar, and other chart types that may be useful in geotechnical engineering practice.

The widespread use of spreadsheet programs in visualizing geotechnical data is a double-edged sword. A spreadsheet program provides powerful calculation and visualization capabilities while being relatively easy to learn. However, the proliferation of spreadsheet files can be a data and file management challenge and difficult to maintain with a high level of quality control. Concern for spreadsheet quality control led to formation of the European Spreadsheet Risks Interest Group (http://www.eusprig.org/index.htm). Although most of the cautionary tales on this website refer to disciplines other than engineering, the lessons learned and advice offered are applicable to geotechnical uses of spreadsheet programs.

BORING LOG GENERATORS

Boring logs are generally the geotechnical engineer's primary method of visualizing and presenting subsurface information. Whether they are soil boring logs, rock core logs, cone penetration test logs, or any of a number of other subsurface explorations, the log typically contains a visual representation of one or more subsurface data elements versus depth or elevation (see Figure 12). This visual representation provides the geotechnical engineer with a first-order analysis of soil or rock layering, groundwater location, and material properties.

A boring log (or other log type) generator is a software program that accepts user data input, stores the data electronically, and outputs a completed log to hard copy or an electronic file. Most boring log generators required that the data be input manually, but some have the capability of accepting data from hand-held mobile devices.

Approximately 40 proprietary and shareware desktop boring log generators are available; although spreadsheet and computer-aided drafting (CAD) programs are also used to generate boring logs. The most comprehensive boring log generators are supported by a desktop or server database and can be used for logs of soil, rock, core penetration tests, and other subsurface explorations.

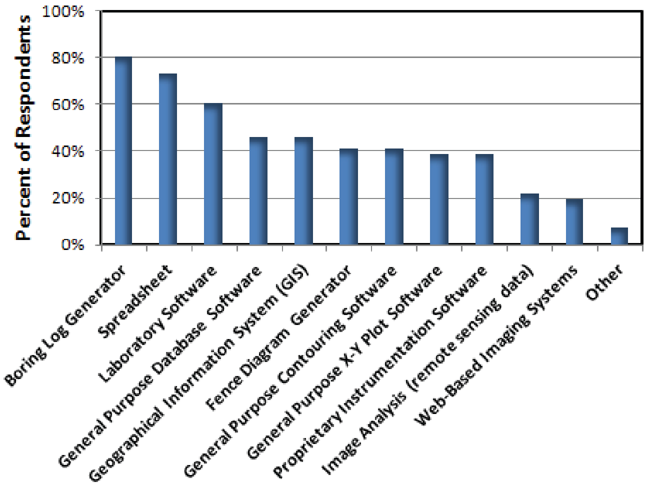

FIGURE 11 Geotechnical data visualization software used.

Approximately 80% of the DOTs surveyed use the same vendor's boring log generator.

FENCE DIAGRAM GENERATORS

The fence diagram is the geotechnical engineer's second-order method of visualizing and presenting subsurface information as it merges the information from several subsurface explorations to create a cross-sectional view of soil or rock layering, groundwater location, and material properties (see Figure 13).

There are a dozen or so proprietary desktop fence diagram generators available to the geotechnical engineer. The ability to generate fence diagrams is integrated with several of the boring log generators described previously.

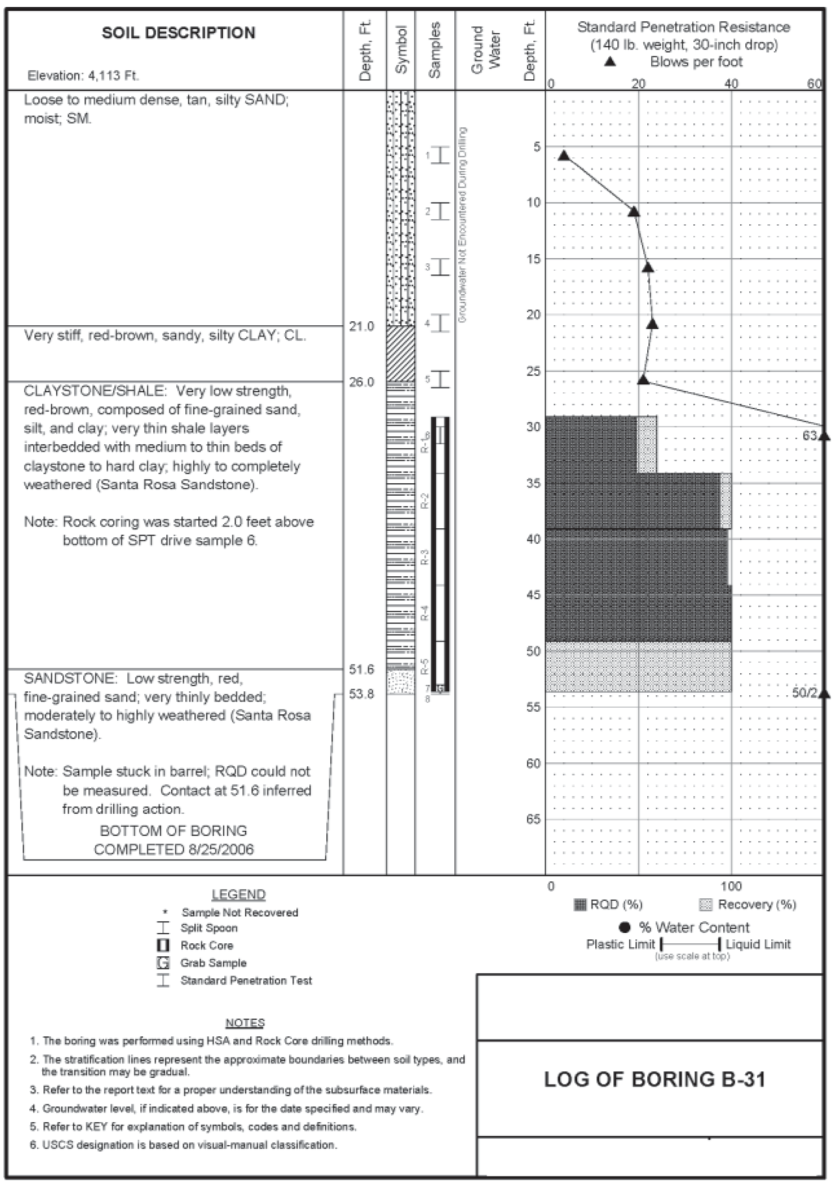

FIGURE 12 Typical boring log.

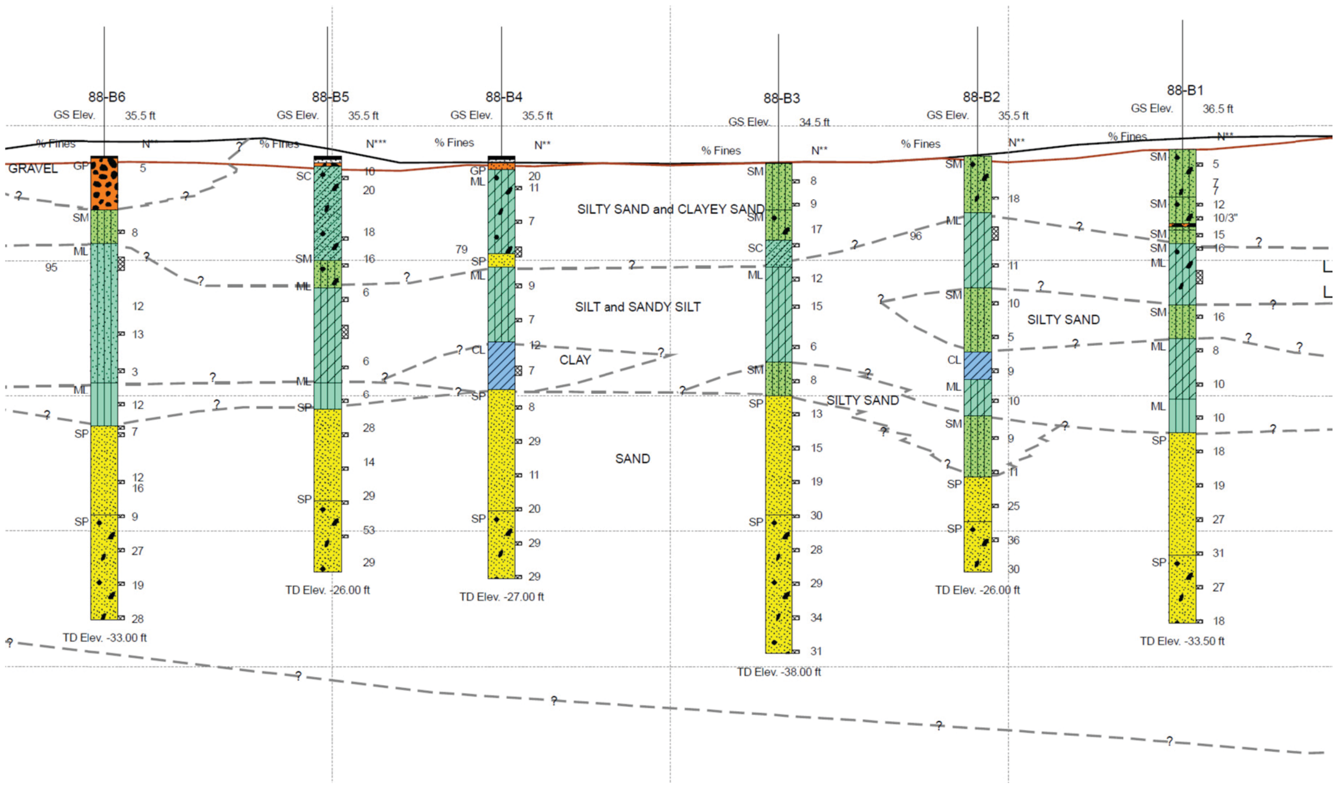

FIGURE 13 Typical fence diagram.

Approximately 70% of the DOTs surveyed use the same vendor's fence diagram generator.

LABORATORY SOFTWARE

Laboratory software includes programs to control laboratory tests, record laboratory data, convert the data to meaningful engineering units, and visualize and present laboratory test results.

More than 80 proprietary desktop laboratory programs are available to geotechnical laboratory technicians and engineers. Some of these programs only calculate the results of a specific test or control and measurement, but many have at least a rudimentary capability to visualize test results. The most comprehensive laboratory programs are supported by a desktop or server database, have strong visualization features, and integrate well with other geotechnical applications.

Approximately 60% of the DOTs surveyed use laboratory software. Despite the wide variety of commercial software available, approximately 20% use department-developed programs or spreadsheets to record, calculate, and visualize their laboratory data.

GENERAL PURPOSE DATABASE SOFTWARE

General purpose database software includes proprietary and open-source programs that efficiently collect, store, and retrieve large quantities of geotechnical data. This software is often used in conjunction with other software applications, such as the boring log generators and laboratory software described previously.

At least a dozen geotechnical-oriented proprietary desktop database programs are available. These applications can be used to store a wide variety of geotechnical data including exploration data, laboratory data, and analytical results. These applications are built on the same proprietary or open-source database engines that underlie many database applications in other disciplines.

About 46% of the DOTs surveyed use general purpose database software to support visualization of geotechnical data. However, no single vendor's software dominates this area.

GENERAL PURPOSE X-Y GRAPHING SOFTWARE

In addition to the ubiquitous spreadsheet, there are more than 100 proprietary and open-source x-y graphing programs available for the desktop or on line. This software is used to visualize data relationships and time trends for field and laboratory data. Some of these programs also have basic statistical analysis capabilities.

About 40% of the DOTs surveyed report using general purpose x-y graphing software; however, approximately half are using spreadsheet software for this purpose.

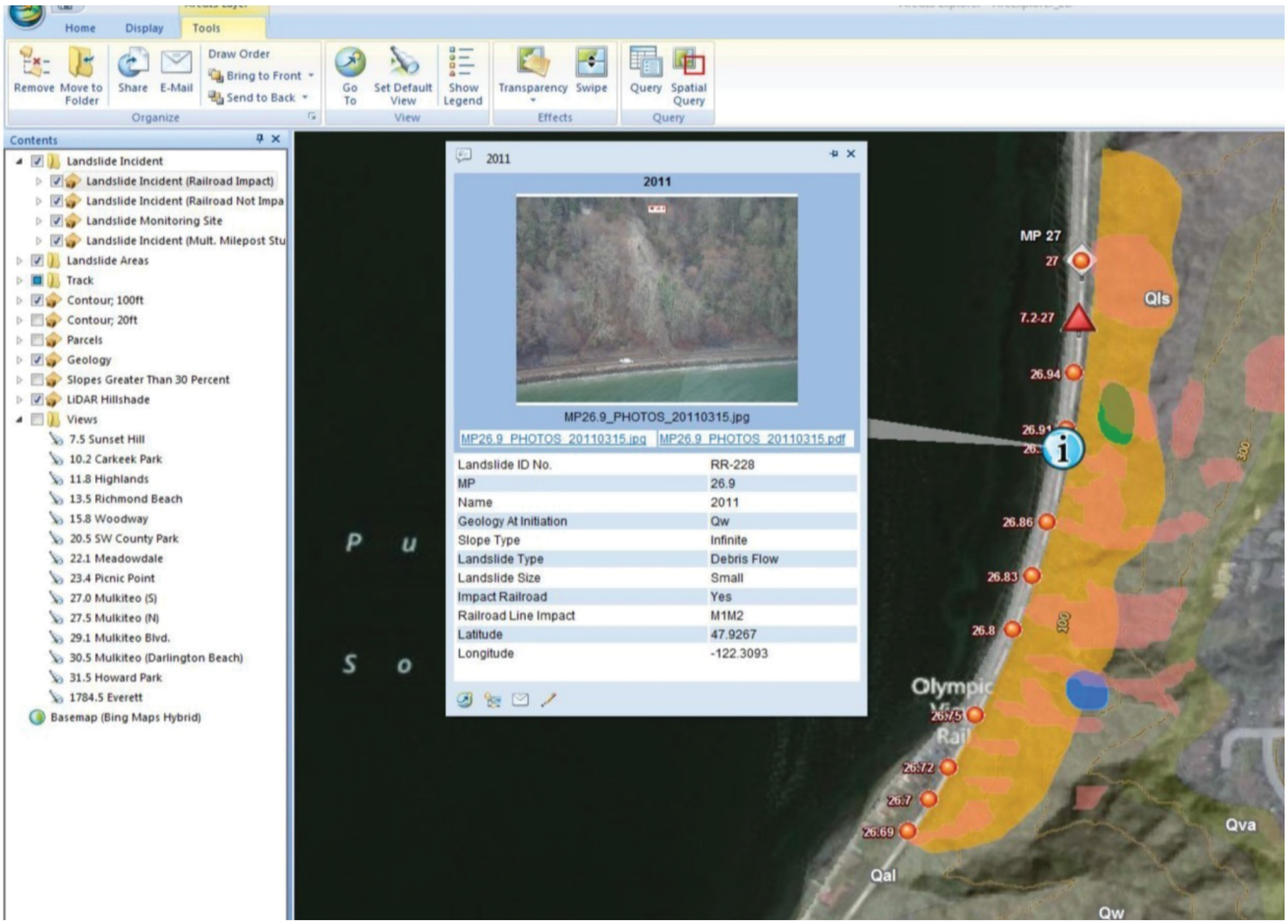

FIGURE 14 Sample GIS application.

GENERAL PURPOSE CONTOURING SOFTWARE

Contouring software is used to visualize three-dimensional data. The most frequent geotechnical use concerns ground surface topography and subsurface contacts, but the contouring is also useful for visualizing multi-dimensional data relationships; for example, contours of limit equilibrium factor of safety against sliding for a range of cohesion and angle of friction values.

Geotechnical engineers have a choice of about two dozen proprietary and open-source contouring programs. The majority of these programs are desktop rather than online applications. The more comprehensive contouring programs have strong visualization features and can import three-dimensional data and support image overlays from a variety of sources.

About 40% of the DOTs are using contouring software. Among those DOTs using contouring software, approximately 35% are using CAD software for this purpose.

GEOGRAPHICAL INFORMATION SYSTEMS

GIS are a class of software that integrates spatial and other data with map-based visualization. GIS applications are especially useful for creating thematic maps and interactive maps that display the data behind the images on the screen.

There are about 20 proprietary desktop and server-based GIS software packages and eight open-source GIS packages. However, one software company currently dominates the GIS market; among the 46% of DOTs using GIS software, only one is using another vendor's software.

The image in Figure 14 illustrates a typical GIS geotechnical application. The colored overlays identify a landslide zone and specific landslides or debris flow events on a bluff above a major commuter and freight railroad. Each red symbol is the location of an investigation of a prior landslide or debris flow event. In the center of Figure 14 is a box providing a photograph and additional information about the event, which can be retrieved by clicking on one of the event location symbols.

INSTRUMENTATION SOFTWARE

Instrumentation software includes programs to schedule, collect, process, and visualize data from an array of field-installed instruments. Some instrumentation software serves a specific instrument type; for example, inclinometer software is often a single purpose application that reduces instrument readings to engineering units and presents the results as a visual representation of displacement versus depth. Other instrumentation software is more general, serving a variety of instrument types and providing at minimum rudimentary graphing capabilities for data visualization.

There are at least 17 proprietary general purpose desktop and web-based instrumentation programs available. All are supported by a database to manage and store the large quantity of data generated by instrumentation arrays. The more comprehensive systems schedule and collect raw instrument data, reduce the data to engineering units, and provide flexible graphing capabilities for visualization.

IMAGE ANALYSIS SOFTWARE

Image analysis software describes a broad class of programs that are used for spectral analysis, spatial pattern analysis, difference analysis, and similar analyses of high resolution images. The software to be used depends heavily on the scale of the images, which can range from thin-section images to satellite images. One of the key applications of image software is difference analysis—a comparison of images of the same location taken at different times. Image analysis software is used to automate the process of finding and highlighting the differences between two images.

At least 10 image processing software packages are available, of which several are open-source packages. Because of the different purposes of image processing and different scales of the images to be processed, it is unlikely that any single image processing package would serve all needs.

About 22% of the DOTs surveyed report that they use image analysis software. The software that they use is a mix of GIS, terrain modeling, and ground penetrating radar (GPR) post-processing software.

WEB-BASED IMAGING SYSTEMS

Web-based imaging systems provide the geotechnical engineer with a convenient, and often inexpensive, method of obtaining air photographs, LiDAR, satellite and other remote sensing images. Public agencies such as USGS, NASA, and other government agencies provide free and low-cost images. Several free, but copyrighted, sites and commercial sites are available as well.

While only about 20% of the DOTs surveyed reported using web-based imaging systems, it is clear that more DOTs are using these systems because of the number of DOTs who report using LiDAR, satellite images, and other remotely sensed data.

OTHER APPLICATIONS

Many geotechnical analysis software packages also include visualization features. For example, software packages for stability, pile capacity, and retaining wall analysis often incorporate useful visualization tools. Finite element and finite difference soil-structure interaction software packages frequently have multiple visualization features including x-y graphing and contouring.

Other potential sources of visualization software are the fields of mineral and energy exploration, biology, and medicine. More effort appears to have been expended to develop data visualization tools in these fields than in the geotechnical field, advances that might be adaptable to GDV uses.

CHAPTER SIX

CURRENT PRACTICE AND EXPERIENCE

The following sections generally describe the state of the practice with respect to visualization of geotechnical data rather than the state of the art. It is evident from the study survey and interviews that the state of the practice encompasses a wide range of experience and tools.

DATA MANAGEMENT

Data management refers to the collection, storage, and retrieval of data. Results of the survey of state geotechnical leaders indicate that most DOTs store their geotechnical data in some combination of paper and electronic files. Among all of the geotechnical data identified by the DOTs, approximately 28% are kept as paper only, 27% are kept in electronic form only, and 45% are kept in both formats. On average, the DOTs keep seven different types of geotechnical data.

The survey also indicates that only about 10% of the DOTs are using a centralized database capable of storing multiple types of geotechnical data. This suggests that many of the DOTs are storing data in isolated, and likely incompatible, formats, making it difficult to visualize related data. For example, laboratory data may be stored separately from boring log or instrumentation data. If these data were stored in a common database, retrieval and visualization of related data would likely be easier to accomplish. Interviews also indicated that re-use of geotechnical information is limited by the lack of a common data format and storage location. Inefficient location and retrieval of historical data often leads to unnecessary replication.

The ability to rapidly access and visualize geotechnical data may not be critical to the success of a geotechnical hazard mitigation project or long-term recovery from a geotechnical disaster; however, during the immediate and short-term response to a geotechnical disaster, speed is essential to organizing rescue efforts, maintaining public safety, and minimizing transportation system impacts. A common database could expedite the retrieval and visualization of critical geotechnical data.

Adopting a standard data interchange format could greatly improve data management for the DOTs, facilitating storage and retrieval of data within the organization and simplifying data delivery for third-party data providers (e.g., drillers, laboratories, consultants). Having a standard data interchange format for geotechnical data also would encourage visualization software developers to incorporate the standard in their products, making GDV simpler to achieve throughout a DOT. Because a number of the state DOTs and the ASCE's Geo-Institute have participated in the development of the DIGGS standard (described later in this chapter), it may be reasonable to assume that DIGGS will eventually become the de facto standard for all state DOTs.

GEOTECHNICAL ANALYSIS

Only a few geotechnical analysis software packages, including slope stability, settlement, retaining wall, and terrain modeling software packages, were identified in the survey of the state DOTs. Because geotechnical analysis software was not the focus of the survey, respondents may not have identified this software as having a significant role in visualization of geotechnical data; however, it can be assumed that the geotechnical engineering staff at the state DOTs use more analytical and numerical software packages than were identified in the survey.

The visualization capabilities of geotechnical analysis software packages are continually improving. This is true with respect to visualization of input parameters and analytical results, but also with respect to parameter entry. Command-line and form-driven parameter entry processes are being replaced by more effective and intuitive graphical interfaces.

INSTRUMENTATION

Geotechnical instruments are a significant source of data for the state DOT geotechnical engineers (see Figure 15). About 95% of the DOTs report using inclinometers; 88% are using piezometers; 83% are using settlement gages; and 73% are using open stand pipe wells on their projects. Other less common instruments include optical and automated surveys, load and displacement gages, and seismometers.

Nearly all (93%) of the state DOT geotechnical leaders report that expert opinion and engineering judgment is a primary driver of the decision to use instruments on a geotechnical project. About one-third of the DOTs use risk analysis methods to support the opinions and judgments. (The study survey did not ask what type of risk methods were used, but presumably they are typical qualitative and quantitative risk assessment and risk management methods.) Only 17% of the DOTs reported that geotechnical instrumentation is required by the

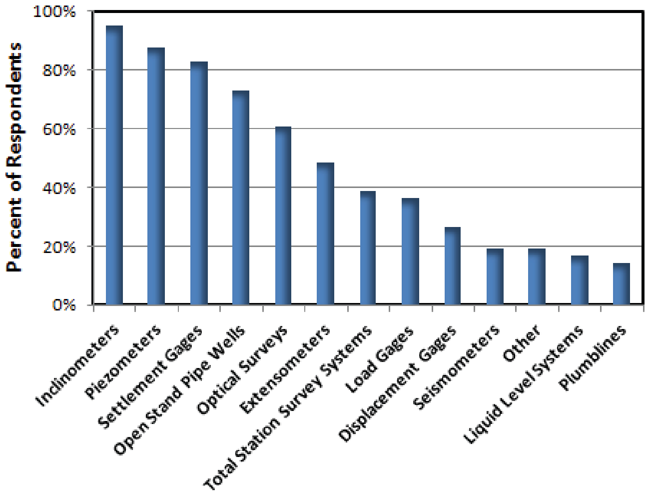

FIGURE 15 Geotechnical instruments used.

department, and that they use expert opinion, engineering judgment, and analysis to determine which instruments to use.

A critical step in using geotechnical instruments is establishing warning and action levels for each instrument. Approximately 90% of the state DOTs reported that expert opinion and engineering judgment are used to set warning and action levels. Nearly 70% use some form of analysis to support the opinions and judgments, and about 40% also use field or laboratory tests. Only about 16% rely solely on opinions and expert recommendations. One respondent noted the potential for adverse consequences arising from instrumentation false alarms. While a low frequency of false alarms is a desirable goal for geotechnical instruments, some understanding of the significance of the instrument readings must be incorporated in any instrumentation system to realize the full value of the data collected.

Geotechnical instrumentation data are collected and stored in a variety of formats, including manual readings recorded on paper, portable recording devices, and highly automated, database-driven systems accessible by the web. Portable recording devices are hand-held, usually battery-powered, and generally require field personnel to connect them to an installed sensor to record a current reading. Data from portable devices are typically uploaded to another system for processing and interpretation. Automated systems are either permanently connected to an array of sensors or can contact the sensors at specified time intervals. In some cases, automated systems can also serve as the data processing and interpretation system or transmit readings directly to another system for processing and interpretation.

Nearly 90% of the DOTs report using manual methods to record instrument data; 70% are using portable electronic devices; and 60% are using automated data acquisition systems. Approximately 40% of the DOTs use two of these collection methods; and 36% use some combination of all three methods.

About 90% of the state DOTs use spreadsheets to manage their instrument data; 53% use vendor software; 22% use department developed software; and about 10% use web-based instrumentation software. Nearly 90% of the DOTs use two or more methods to manage their instrument data. The variety of formats used to store and retrieve data is very likely a significant obstacle to the efficient and effective visualization of instrumentation data in the DOTs.

REMOTE SENSING DATA

Nearly 80% of the state DOTs use air photography, and about 60% use LiDAR, topographic data, and satellite images (see Figure 16). About 25% use some form of radar data; for example, synthetic aperture radar (SAR), interferometric synthetic aperture radar (inSAR), or GPR. Less than 5% report using thematic data. The typical DOT uses three to four different forms of remotely sensed data and images.

The primary sources the DOTs use for remotely sensed data are free websites, department generated data, and the USGS. About 60% of the DOTs use these sources. About 25% of the DOTs use commercial and U.S. Department of Agriculture data.

HAZARD MITIGATION

The state DOT geotechnical leaders report that data visualization is used in nearly all aspects of geotechnical hazard mitigation; 60% to 70% report using GDV in identifying, assessing, monitoring, analyzing, designing, and constructing hazard mitigation measures. The importance of GDV in the development and implementation of these measures is also widely noted: About 60% of the DOTs reported it has contributed to better identification, assessment, monitoring, analysis, and design of geotechnical hazard mitigation measures.

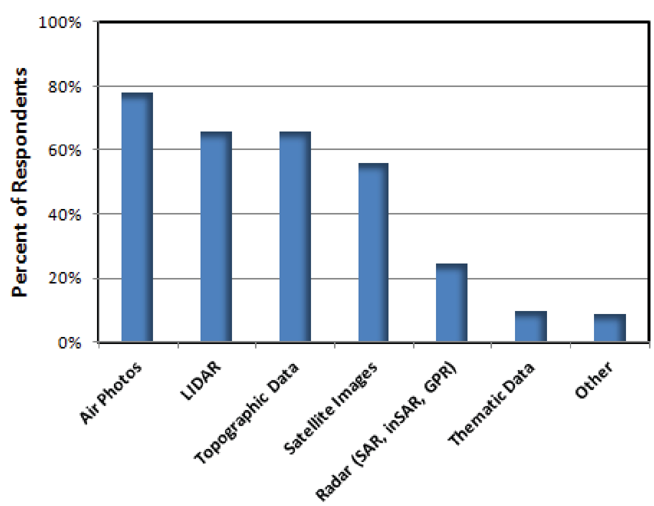

FIGURE 16 Remotely sensed data usage.

More than 70% of the DOTs report having used GDV in the successful mitigation of unstable embankments and landslides; 50% to 55% of the DOTs have used it in the successful mitigation of settlement or heave hazards and rockfall hazards; and about 40% of the DOTs have used visualization in the successful mitigation of sinkhole hazards. Fewer DOTs have had to mitigate other geotechnical hazards, such as slope creep, debris flows, avalanches, and frost heave; but GDV has contributed to such efforts.

However, visualization of geotechnical data is not a guarantee of successful hazard mitigation. About 20% of the state DOT geotechnical leaders report that they have been unsuccessful in mitigating one or two types of geotechnical hazards; and the unsuccessfully mitigated hazard types are often the same as the successfully mitigated ones.

Approximately 70% of the DOTs report that GDV has helped in implementing measures to improve public safety; 35% to 40% believe that visualization has helped improve worker safety and traffic mobility; and 20% believe that visualization has helped improve the speed of implementing hazard mitigation measures.

DISASTER AND EXTREME EVENT RESPONSE

Visualization of geotechnical data during disaster or extreme event response is limited at many of the state DOT geotechnical divisions. Only about 30% of the DOTs report having disaster-ready visualization access to such basic geotechnical data as boring logs, geologic maps, and geotechnical reports. In spite of these apparent limitations, about 60% of the DOTs use visualization of geotechnical data in damage assessment, safety analysis, and temporary repair design when responding to geotechnical disasters or extreme events. Between 40% and 50% have used GDV during construction of temporary repairs and to maintain public and worker safety; and 20% to 30% have used GDV to facilitate communication, coordination, and traffic control.

The relatively widespread use of GDV following disasters or extreme events indicates the value placed on it in such circumstances. This is supported by the large percentage of DOT geotechnical leaders who would find almost all geotechnical data useful during disaster response; about 80% reported that they would find boring logs, geotechnical reports, groundwater data, as-built drawings, geologic maps, and pre-event photographs helpful.

LONG-TERM DISASTER RECOVERY

Long-term disaster recovery refers to activities undertaken well after the emergency response period, including the planning, design, and construction necessary to remediate the damages and to at least restore the transportation system to its pre-disaster safety and functionality. Long-term recovery often affords a transportation agency the opportunity to build a more resilient system than existed previously. About 87% of the state DOT geotechnical leaders report that they use GDV during the design phase of long-term disaster recovery; 60% to 70% report that they use visualization during assessment, planning, analysis, and construction of long-term remediation measures.

The state DOT geotechnical leaders' responses to this survey question were generally similar to their responses to the same question in the context of geotechnical hazard mitigation. The exception to this generalization is in the design phase; 75% of the DOTs report using GDV in the design of hazard mitigation measures, whereas 87% report using visualization in the design of long-term disaster recovery measures. The responses may imply that geotechnical hazard mitigation and long-term disaster recovery are similar processes that do not have the urgency associated with disaster response, and that consequently, the DOTs have more time to retrieve and visualize geotechnical data.

The DOTs were asked to indicate how GDV affects their ability to achieve a more efficient and effective recovery from a transportation disaster. About 70% responded that using GDV during long-term recovery from a disaster led to a more economic design and construction process; about 65% of the DOTs reported that visualization contributed to improved public safety; and approximately 60% said that visualization led to a more rapid recovery. Just over 40% of the DOTs noted that visualization led to improved worker safety and about 25% said it improved public communication and recovery of traffic mobility.

VISUALIZATION USAGE AND EXPERIENCE

The final section of the study survey asked the state DOT geotechnical leaders to do a self-evaluation of their use of and experience with GDV tools in order to gauge the current level of their expertise in applying these tools to solving the hazard mitigation, disaster response, and disaster recovery challenges they face.

About 29% of the state DOT geotechnical leaders reported that their organization is a frequent user of GDV tools; approximately 37% are occasional users; and about 29% of the DOTs use these tools only rarely. One DOT (2%) never uses these tools, and another did not know its organization's level of use. The total of about 66% who are frequent or occasional users is generally consistent with the overall level of usage that can be inferred from the responses to other questions in the survey.

Among the DOTs that do use GDV tools, just over half consider their organization to be at an entry level of expertise, about one-third are at an intermediate level, and 12% consider their organization to be at an expert level. A previous study of DOT usage of advanced geospatial tools (Olsen et al. 2013) concluded that a higher level of expertise exists in the DOTs than the current study would imply; however, that study survey targeted geospatial and "other relevant contacts" within the DOTs, whereas the current study survey targeted the DOT geotechnical leaders. It is reasonable to assume that a DOT's geotechnical staff may rely on other staff within the organization to provide a high level of visualization expertise.

The state DOT geotechnical leaders were asked to rank their agreement or disagreement with the following three statements:

- GDV improves our ability to mitigate geotechnical hazards.
- GDV improves our ability to respond to geotechnical disasters.
- GDV improves our ability to achieve long-term recovery from geotechnical disasters.

The responses were remarkably consistent, with 90% to 93% of the DOTs agreeing or generally agreeing with all three statements. This implies that the state DOT geotechnical leaders understand the purpose and value of data visualization even if they may not yet have the tools and expertise to take full advantage of it.

VISUALIZATION USERS

Almost 90% of the state DOTs report that their geotechnical engineering staff is using GDV tools, and nearly 70% report that their staff geologists use these tools. Between 15% and 25% of the DOTs said that managers, planners, designers, laboratory staff, and other engineering disciplines use GDV tools, but fewer than 5% report that first responders to geotechnical disasters use these tools.

Based on the types of software that the state DOT geotechnical leaders identified as being used in their organizations, it can be assumed that most geotechnical personnel are proficient with one or more applications (e.g., spreadsheet, boring log generator, instrumentation software). However, with the exception of those few state DOTs that use a centralized database, most geotechnical personnel likely do not have easy visual access to all of the available geotechnical data.

VISUALIZATION ISSUES

Responses to the study survey indicate that usage of a geotechnical data interchange standard within the individual state DOTs is limited. Use of a geotechnical data interchange standard would simplify the collection, processing, and retrieval of geotechnical data for rapid visualization.

A data interchange format is a specification of a structured data file based on the open-source Extensible Markup Language (XML) produced by the World Wide Web Consortium. The human and machine-readable file contains the data in a specified order, a description of the data, and a description of the data sequence within the file.

The advantages of a data interchange format are that the data generator knows how to deliver the data; the software developer understands how to read the data; multiple users can read and use the same data; and data quality is maintained at every step. This concept has been successfully applied by the EPA in its Staged Electronic Data Deliverable (SEDD) standard. The land surveyors and architects have used landXML, an XML-based data interchange format, to collect, process, and share surveying and civil engineering data since 2000.

At least three XML-based data interchange formats have been proposed for geotechnical data, including:

- Data Interchange for Geotechnical and Geoenvironmental Specialists (DIGGS, www.diggsml.com)
- Spatial Data Standard for Facilities, Infrastructure, and Environment (SDSFIE, www.sdsfieonline.org)
- Association of Geotechnical and Geoenvironmental Specialists (AGS, www.ags.org.uk).

The SDSFIE format is a U.S. Department of Defense standard; AGS is a standard developed in the United Kingdom (UK); and DIGGS was developed by a group that includes the FHWA, U.S. Army Corps of Engineers, EPA, USGS, the UK Highway Agency, and 11 state DOTs.

Among the issues raised during the study interviews was that reliability and scale are critical considerations for the use of GDV. Using flawed visualization tools or data to make decisions about geotechnical hazard mitigation or disaster response may make the situation worse rather than better.

The data underlying any visualization, geotechnical or otherwise, must meet the reliability criteria of completeness, correctness, timeliness, and integrity:

- Completeness refers to the percentage of relevant information contained in the data. For example, one might catalog all of the exposed joints in a rock mass, but the data set may be incomplete because of hidden joints.
- Correctness refers to the accuracy and consistency of the data. The depth to groundwater, for example, is typically measured at a few locations to the nearest 0.1 foot with some degree of measurement uncertainty. The few measurements are then projected between locations, adding another level of uncertainty.
- Timeliness refers to the age of the data. The passage of time can add uncertainty to the most complete and correct measurements.
- Integrity refers to the steps taken to ensure that the data remains complete and correct.

The criteria may not require 100% completeness or correctness; it is difficult to collect and maintain any type of data, and especially geotechnical data, without some level of uncertainty. However, the inherent uncertainty in the data must be understood by the user and, preferably, be displayed in the visualization. For example, it is not uncommon to see error bars or error bands on an x-y plot, but it is rare to see a contour plot or LiDAR image with a visual or textual expression of the uncertainty associated with the plot or image.

The issues of geotechnical data reliability extend to the software and hardware used to visualize the data. For example, x-y-z contouring software provides a surface projection based on a finite number of measurement points. A value taken from an arbitrary point on the surface has an associated uncertainty that is a combination of data and projection uncertainties. Hardware can also be problematic: For example, if the resolution of the user's screen or printer is much different than the resolution of the underlying data, the user may "see" distinctions that are not supported by the underlying data or may miss important information.

Scale issues arise in GDV because geotechnical data are measured at scales ranging from particle size to satellite images. Although no one is likely to attempt to integrate geotechnical data from the entire scale range into a single visualization, it is possible that someone could be interested in, say, site-specific to corridor-level visual integration. In such a case, the user must be aware of problematic factors in larger scale visualizations—e.g., that the level of uncertainty associated with corridor level data may overshadow more precise, site-specific data.

CHAPTER SEVEN

CURRENT RESEARCH AND DEVELOPMENT

ACADEMIC RESEARCH AND DEVELOPMENT

The breadth and depth of academic R&D bodes well for the future of GDV. For example:

- The University of Utah's Scientific Computing and Imaging Institute's visualization projects include modeling, display, and understanding uncertainty for policy decision making; situational awareness visualization; and more general studies of uncertainty visualization.
- One focus of Marshall University's Center for Environmental, Geotechnical and Applied Sciences is visualizing geohazards and their impacts on society, including impacts on transportation systems.
- The Civil Engineering Geomatics research group at Oregon State University integrates geomatics engineering, computer science, geotechnical engineering, and geology to analyze hazards in civil engineering. Its focus is on applications of terrestrial laser scanning and geographic information systems.
- Focusing on a smaller scale subject, the University of Michigan's Geotechnical Research and Visualization Engineering Laboratory is developing advanced visualization software and hardware for soil characterization.
- Temple University's Coe Geotechnical Research Group is studying laboratory- and field-scale non-destructive and geophysical methods for visualizing the subsurface and their applications to geotechnical issues related to development, rehabilitation, and maintenance of infrastructure systems.

Among other universities actively engaged in research and development in the area are Columbia, Harvard, Iowa State, and Louisiana State; the universities of Alaska, Florida, Illinois, Kentucky, Virginia, and Washington; the University of California-Davis, the Massachusetts Institute of Technology, Rensselaer Polytechnic Institute, Michigan Technological University, and Virginia Polytechnic Institute and State University.

As suggested by this small sampling, current academic R&D will likely have near-term benefits for the practicing geotechnical engineer. In addition, there is much academic research underway to resolve more fundamental visualization issues such as better algorithms, better hardware, and, perhaps most importantly, better human-machine interfaces. The human-machine interface includes the hardware (keyboards, pointers, and screens) and visible portion of the software that we use to enter data, control processing, and generate the text and images needed to understand and solve the problem at hand. Better algorithms are needed to process the larger and larger data sets being encountered; better hardware is needed to quickly and accurately display the underlying data; and better human-machine interfaces are needed so that users can retrieve important information and arrive at decisions more confidently and quickly.

COMMERCIAL DEVELOPMENT

The following quote (Moore, 2010) generally characterizes the commercial software industry.

> For me the difference between **Technology** and **Product** is the motivation for writing them: **Technology** is written because it is interesting, cool, solves a problem in an innovative way and pushes our understanding of computer science further . . . some of this technology will turn into massively successful commercial software but this is often done as an afterthought or as a reaction to a highly successful piece of research. **Product** is written to be sold. A potential set of buyers are identified and software is written with the sole purpose of selling to that target market . . . [For] a commercial organization there is little or no intrinsic value in the software itself, the value is in the product.

While the visualization capabilities of geotechnical software continue to improve with respect to visualization of input parameters, analytical results, and visual parameter entry, the primary motive of commercial software development is profit. The software vendors interviewed noted that product development is generally customer- and competitor-driven. Customer-requested changes and improvements push geotechnical software development; but keeping pace with or staying ahead of competitors, and thereby maintaining market share, is a significant factor in vendor software development.

Geotechnical engineers in transportation might also look outside their discipline for applications that could be adapted to visualization of geotechnical data (Figure 17). For example, software developers in the mineral and energy exploration industry have developed powerful tools for visualizing the subsurface based on boring log and remote sensing data. The medical profession's two- and three-dimensional visualization tools for remotely sensed human data may also be a model or

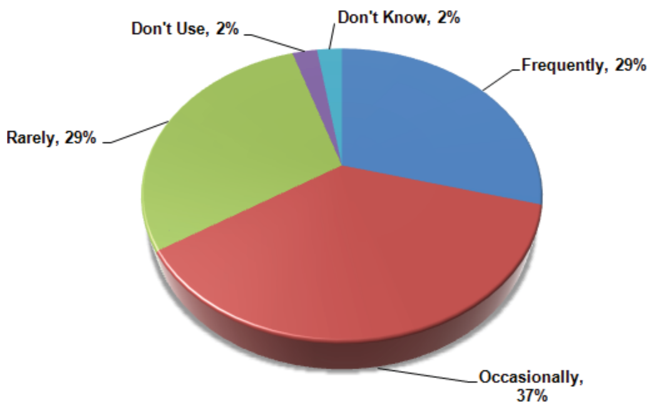

FIGURE 17 Use of geotechnical data visualization tools for disaster or extreme event response.

resource for software and techniques that can be used in the visualization of geotechnical data (Figure 18).

OPEN-SOURCE DEVELOPMENT

Developers of open-source geotechnical software are focused primarily on analytical tools rather than visualization tools. The open-source geotechnical analytical software packages generally have some visualization capabilities, but the visualization features are less well developed than in comparable commercial software packages (e.g., OpenSees, the Open System for Earthquake Engineering Simulation http://opensees.berkeley.edu/) (Figure 19). Open-source software designed specifically for visualization is much more sophisticated, but is not well integrated with geotechnical data (e.g., VisIt, developed by the DOE Advanced Simulation and Computing Initiative, http://visit.llnl.gov).

A drawback of some open-source software is that it is developed and maintained in an academic environment in which the focus of improvements and changes can be on research rather than practical applications.

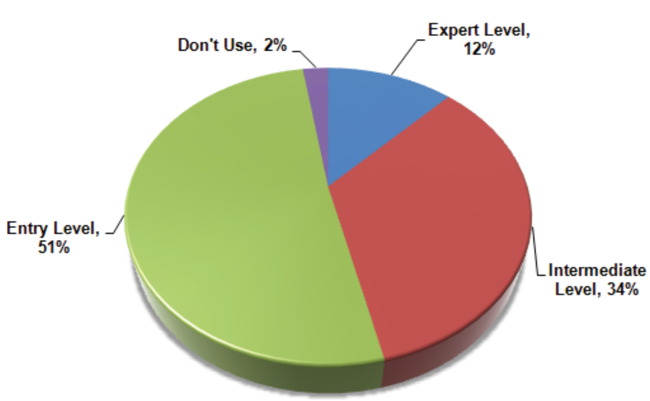

FIGURE 18 Level of use of geotechnical data visualization.

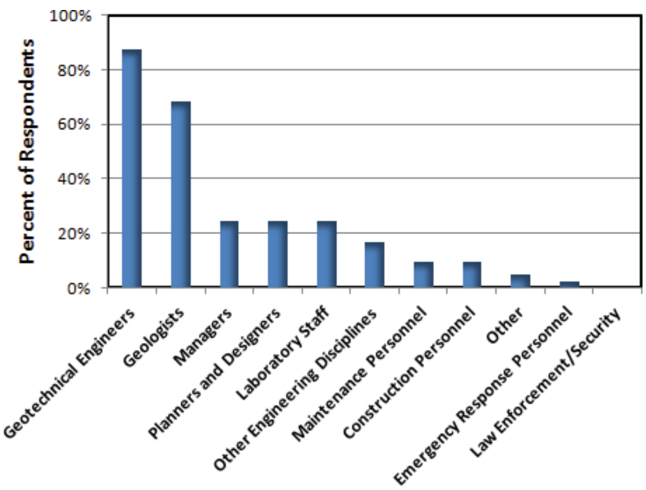

FIGURE 19 Geotechnical data visualization software users.

INNOVATIVE TECHNOLOGIES

Innovative technology, sometimes called disruptive innovation (Christensen 1997), refers to technical developments that create a significant shift in how or how fast a task is completed. Innovative technologies are often thought of as having a radical and immediate impact, but can be incremental as well. Some innovative technologies put an end to previous technologies, some enhance existing ones. One frequently cited innovative technology in the geotechnical engineering world was the development of microprocessors that led to the hand-held calculator and the demise of the slide rule. Subsequent microprocessor development led to the personal computer and unprecedented computing power at every engineer's desk.

A few innovative technologies that could potentially impact data visualization for geotechnical hazard mitigation and disaster response include unmanned aerial systems (UAS), situational awareness visualization, "big data" management, and smart devices.

Unmanned aerial systems, commonly referred to as "drones," have potential for remote sensing applications and visual inspection of hazards and disasters. UAS are more mobile and generally less expensive that other airborne remote sensing systems and, therefore, have the ability to provide more focused and near-real time collection of three-dimensional point cloud data. The use of UAS for visual inspection of hazards and disasters is being explored by NASA for its Western States Fire Mission http://www.nasa.gov/centers/dryden/history/pastprojects/WSFM/index.html. Similar UAS have also been used for safer and closer inspection of geotechnical hazards and disasters.

Situational awareness is described by three components: perception of all temporal and spatial elements of a situation; understanding the relationships among these elements;

and projection of that understanding into the near future. The study and application of these concepts has been part of such fields as military command and control, air traffic control, and civilian emergency response for many years; but recent research has begun to suggest how they might be applied to visualizing the elements of situational awareness, which requires the rapid integration of many types of data from multiple sources—including the possibility of incorporating geotechnical data in the immediate response to geotechnical disasters and extreme events.

"Big data" refers to the explosion of information facing geotechnical engineers. Data are constantly increasing in volume, variety, and velocity (the speed at which data accumulate). The new software methods of managing, retrieving, visualizing, and interpreting large data sets that are being developed and applied in disciplines outside of geotechnical engineering are gradually being adapted for and adopted by the geotechnical profession.

The proliferation of "smart" devices (phones, pads, tablets, etc.) provides another opportunity for innovative application of technology to geotechnical disaster response. An individual with a smart device can witness, report, and record events as they occur. Using social media or other communication channels, these "eyes on the ground" could provide invaluable reconnaissance data to disaster response teams. Dashti et al. (2014) evaluated this method of data collection during the 2013 floods in Colorado. Dashti noted that "much of the data about infrastructure performance and the progression of geological phenomena are lost during the event or soon after as efforts move to the recovery phase." Smart device users can provide these data, but the challenge will be to filter, interpret, and validate this uncontrolled, ad hoc data source.

CHAPTER EIGHT

CONCLUSIONS AND RESEARCH OPPORTUNITIES

CONCLUSIONS

This study summarizes the use and value of data visualization for geotechnical hazard mitigation and disaster response in the transportation profession. The objectives of the study were to quantify the nature and number of geotechnical hazards and disasters facing transportation personnel, determine what types of geotechnical data and visualization tools are available to them, and evaluate the effectiveness of the geotechnical data visualization (GDV) tools they use.

The study is based on a literature review, interviews with selected rail and pipeline geotechnical leaders, interviews with visualization research and development (R&D) leaders in academia, interviews with geotechnical software vendors, and a survey of the state department of transportation (DOT) geotechnical leaders. Completed survey responses were received from 40 of the 50 state DOT geotechnical leaders and from the DOT geotechnical leader in Puerto Rico. An additional five state DOTs provided partial responses. Key findings of the study are summarized here:

The natural phenomena hazards that threaten transportation systems throughout the United States include hazards of geological origin, but are dominated by meteorological hazards. Extreme precipitation, extreme temperatures, and high winds are the most frequently occurring natural phenomena hazards.

Nearly every type of geotechnical hazard threatens transportation systems, but the most common are landslides, rock falls, and embankment failures. The most costly hazards are landslides, rock falls, and sinkholes. The state DOTs are faced with more hazards than they can reasonably and economically address, and they are acutely aware of the social and political damage that often accompanies a geotechnical disaster.

Traditional geotechnical, instrument, and remote sensing data are collected and retained, but some DOTs have yet to implement systems to readily access and visualize the data. The complexity and pace of development of new GDV technology and methods will be a significant challenge to the DOTs and to other transportation sectors for the foreseeable future.

Most DOTs report that geotechnical hazard mitigation is generally successful and that visualization of geotechnical data has an important role in identifying hazards and implementing mitigation measures. Visualization tools are generally used in all aspects of hazard mitigation development and implementation, including identification, monitoring, design, and construction of the mitigation measures.

Most geotechnical leaders would like to have a substantial amount of geotechnical data available online and on site during geotechnical disaster response, but relatively few have the systems to accomplish this goal. The geotechnical leaders in every transportation sector identify speed as the essential element of disaster response. Their challenge is developing systems and data that could provide critical GDV with the speed and simplicity necessary for disaster response.

When available, visualization of geotechnical data has an important role in responses to geotechnical disasters. Visualizations improve damage assessment, design and implementation of repairs; and contribute to maintaining public and worker safety.

Visualization of geotechnical data has a role in long-term recovery from geotechnical disasters that is very similar to its role in hazard mitigation. Visualization tools are generally used in all aspects of long-term recovery development and implementation, including analysis, design, and construction of the recovery measures. Visualization of geotechnical data contributes to more economical design, improved public and worker safety, and faster recovery.

In addition to funding limitations for GDV tools, there appears to be some institutional resistance in the transportation sector to adopting new tools and methods. These tools may be viewed as unjustifiably expensive or as a threat to established personnel and procedures. Geotechnical leaders in transportation, especially in the public sector, must use their position and authority to overcome these challenges.

RESEARCH OPPORTUNITIES

The results of the study survey and interviews suggest a number of research opportunities, including:

- Geotechnical hazard identification and prioritization
- Geotechnical data standards and data interchange formats
- The human-machine interface.

Geotechnical Hazard Identification and Prioritization

Natural phenomena and geotechnical hazards are generally well understood by the geotechnical leaders in transportation; but additional research is needed to identify and prioritize all significant geotechnical hazards in transportation systems—a particular challenge because many of the hazards are hidden from view and may not be recognized until disaster strikes. Research into geotechnical hazard identification should be focused on improving methods of subsurface investigation and additional application of remote sensing technologies. Geotechnical hazard prioritization research could focus on understanding the likelihood of a hazard's becoming a geotechnical disaster and on methodologies to prioritize a diverse range of hazards.

Many state DOTs have undertaken an inventory of selected geotechnical hazards; for example, in Alaska, of its unstable slope inventory. However, additional research is needed to identify all significant geotechnical hazards, evaluate their potential consequences, and perform a risk analysis to provide a consistent and defensible prioritization for the limited geotechnical hazard mitigation funding that is available.

The importance of additional research for geotechnical hazard identification and prioritization is underscored by a recent study of the grand challenges in civil engineering (Becerik-Gerber et al. 2014). In this study of civil engineering disciplines, including architectural, coastal, environmental, transportation, structural, geotechnical, and construction engineering, 10 of the 27 challenges were related to transportation and directly or indirectly related to geotechnical engineering. Three of the top 10 grand challenges are directly or indirectly related to transportation and geotechnical engineering. The top 10 grand challenges were determined by examining the economic, environmental, and societal impacts of each identified challenge.

Geotechnical Data Standards and Data Interchange Formats

Geotechnical data is a diverse mix of numeric, text, and imaging data coming from field investigation, laboratory testing, analysis, design, construction, and maintenance records. Although several approaches to standardizing the collection, storage, transmission, and use of geotechnical data have been developed and proposed to the geotechnical profession, none of these proposals has yet received widespread acceptance. Additional R&D is needed to create a geotechnical data standard that is comprehensive and understandable; and to develop a data interchange format that can be readily implemented by data generators, software developers, and the geotechnical engineering community. In addition to the benefits of data transparency, consistency, and communication, the adoption of a geotechnical data standard and data interchange format would greatly facilitate the development and application of GDV tools.

The development of the DIGGS data interchange format has progressed slowly, but action has been taken by the Geo-Institute of the ASCE to revitalize this standard (Bachus 2014). To be successful, any additional R&D of data standards and data exchange formats must be coordinated among the geotechnical data generators, software vendors, the geotechnical engineering community, and the various agencies that might sponsor and fund the effort.

The Human–Machine Interface

Among the GDV topics currently being pursued academically and commercially, the most important may be R&D of better human–machine interfaces. The human–machine interface includes the devices such as keyboards, pointers, and screens as well as the visible portion of the software used to enter data, control processing, and generate the text and images needed to understand and solve the problem at hand.

Geotechnical engineers in all sectors, not just in transportation, are faced with an ever-growing array of computing and visualization tools. The different human-machine interfaces found in almost every tool adds another level of complexity to the engineer's work load. The advent of "big data" in the geotechnical profession adds an even greater challenge. Using yesterday's tools to manage and visualize today's data volume, variety, and velocity would be a frustrating and unreliable undertaking. This trend is not limited to geotechnical engineering; other industries are using data analytics to improve business operations and for complex decision support. Additional research might be undertaken to simplify and standardize GDV tool interfaces.

While the data analytics research topic is not typical geotechnical engineering research, it is important that this research be conducted with input from practicing geotechnical engineers. Consequently, this research will likely need to be a joint effort among the geotechnical and software/hardware engineering communities.

ABBREVIATIONS

DIGGS	Data interchange for geotechnical and geoenvironmental specialists
DOT	Department of transportation
GIS	Geographic information system
GDV	Geotechnical data visualization
GIS	Geographical information systems
GPR	Ground penetrating radar
LiDAR/lidar	Light detection and ranging
R&D	Research and development
UAS	Unmanned aerial systems
USGS	U.S. Geological Survey
XML	Extensible markup language

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APPENDIX A

Survey Questionnaire

Survey Questionnaire

1.01 **What natural phenomena hazards do you encounter?** Check all that apply and add additional items in the space provided.

- [ ] Earthquakes
- [ ] Volcanoes
- [ ] Floods
- [ ] Tsunamis
- [ ] Extreme Precipitation (Rain or Snow)
- [ ] Extreme Temperatures
- [ ] Freezing/Thawing Ground
- [ ] Hurricanes, Tornados, or Other High Velocity Winds
- [ ] Storm Surges
- [ ] Other

1.02 **What geotechnical hazards do you encounter?** Check all that apply and add additional items in the space provided.

- [ ] Landslides
- [ ] Embankment Failures
- [ ] Rock Falls
- [ ] Debris Flows
- [ ] Avalanches
- [ ] Slope Creep
- [ ] Wind Blown Soil/Dunes
- [ ] Settlement or Heave
- [ ] Lateral Spreading
- [ ] Surface Ruptures
- [ ] Subsidence
- [ ] Sinkholes
- [ ] Permafrost Thaw/Freeze
- [ ] Frozen Debris Lobes
- [ ] Other

1.03 **What geotechnical disasters have you had to respond to?** Check all that apply and add additional items in the space provided.

- [ ] Landslides
- [ ] Embankment Failures
- [ ] Rock Falls
- [ ] Debris Flows
- [ ] Avalanches
- [ ] Slope Creep
- [ ] Wind Blown Soil/Dunes
- [ ] Settlement or Heave
- [ ] Lateral Spreading
- [ ] Surface Ruptures
- [ ] Subsidence
- [ ] Sinkholes
- [ ] Permafrost Thaw/Freeze
- [ ] Frozen Debris Lobes
- [ ] Other

1.04 **Which hazard, disaster, or extreme event types do you most frequently encounter?**

1.05 **Which hazard, disaster, or extreme event types are most detrimental to your organization's finances and**

Survey Questionnaire

reputation?

SECTION 2. GEOTECHNICAL DATA MANAGEMENT

2.01 **What geotechnical data does your organization keep on paper file?** Check all that apply and add additional items in the space provided.

- Geologic Maps
- Boring / Well Logs
- Laboratory Test Results
- Groundwater Data
- Subsurface Profiles
- Geotechnical Reports
- Instrument Monitoring Reports
- Corridor Maps / Air Photos
- Design Drawings
- As-Built Drawings
- Construction Logs
- Maintenance Logs
- Extreme Event Reports
- Pre-Event Photos
- Data From Other Sites
- Other

2.02 **What geotechnical data does your organization keep in electronic format suitable for visualization?** Check all that apply and add additional items in the space provided.

- Geologic Maps
- Boring / Well Logs
- Laboratory Test Results
- Groundwater Data
- Subsurface Profiles
- Geotechnical Reports
- Instrument Monitoring Reports
- Corridor Maps / Air Photos
- Design Drawings
- As-Built Drawings
- Construction Logs
- Maintenance Logs
- Extreme Event Reports
- Pre-Event Photos
- Data From Other Sites
- Other

2.03 **Does your organization have a centralized electronic database for any or all of the geotechnical data listed in Question 2.02?**

- Yes
- No
- Don't Know

2.04 **If yes to question 2.03, how long is the data retained?**

- 1-2 Years
- 5-10 Years
- Other

Survey Questionnaire

- 2-5 Years
- Permanently

2.05 **If yes to question 2.03, what database do you use?** Please specify database in "Comments" space below.

- Department Developed Database
- Commercial Database
- Open Source Database

Comments

2.06 **Do you use a formal geotechnical data exchange format?**

- Spatial Data Standard for Facilities, Infrastructure, and Environment (SDSFIE, DoD)
- Data Interchange for Geotechnical and GeoEnvironmental Specialists (DIGGS)
- Association of Geotechnical and Geoenvironmental Specialists (AGS)
- No Formal Exchange Format Used
- Don't Know
- Other

2.07 **What geotechnical instrumentation does your organization use?** Check all that apply and add additional items in the space provided.

- Open Stand Pipe Wells
- Piezometers
- Inclinometers
- Settlement Gages
- Displacement Gages
- Load Gages
- Extensometers
- Plumblines
- Liquid Level Systems
- Optical Surveys
- Total Station Survey Systems
- Seismometers
- Other

2.08 **On what types of projects do you use geotechnical instrumentation?** Check all that apply and add additional items in the space provided.

- During New Construction
- Long Term, Post-Construction
- Hazard Monitoring
- Foundations, Subgrade
- Pavement
- Bridges
- Other

Survey Questionnaire

2.09 **How is the decision to use geotechnical instrumentation made?** Check all that apply and add additional items in the space provided.

- ☐ Required by Department
- ☐ Risk Analysis
- ☐ Expert Opinion and Engineering Judgment
- ☐ Other

2.10 **How do you collect geotechnical instrumentation data?** Check all that apply and add additional responses in the space provided.

- ☐ Manual Readings
- ☐ Automated Data Acquisition Systems
- ☐ Portable Electronic Devices
- ☐ Other

2.11 **How do you establish hazard mitigation warning and action levels for geotechnical instrumentation data?** Check all that apply and add additional responses in the space provided.

- ☐ Field Tests
- ☐ Laboratory Tests
- ☐ Analysis
- ☐ Expert Opinion and Engineering Judgment
- ☐ Other

2.12 **How do you store and process geotechnical instrumentation data?** Check all that apply and add additional responses in the space provided.

- ☐ Spreadsheets
- ☐ Department's Central Database
- ☐ Vendor Software and Database (please specify name in "Comments" below)
- ☐ Web-Based Software and Database (please specify name in "Comments" below)
- ☐ Other

Comments

Survey Questionnaire

2.13 **What remote sensing data does your organization use for geotechnical mapping and monitoring?** Check all that apply and add additional items in the space provided.

- ☐ Air Photos
- ☐ Satellite Images
- ☐ LIDAR
- ☐ Topographic Data
- ☐ Radar (SAR, inSAR, GPR, etc.)
- ☐ Thematic Data (e.g. soil type, moisture)
- ☐ Other

2.14 **Where do you obtain remote sensing data for geotechnical mapping and monitoring?** Check all that apply and add additional items in the space provided.

- ☐ Commercial Sources
- ☐ USGS
- ☐ USDA
- ☐ Google or Bing Maps
- ☐ Google Earth
- ☐ COSMOS
- ☐ NASA
- ☐ Generated by Department Staff
- ☐ Other

2.15 **What geotechnical data visualization software does your organization use?** Enter name of software that you use in the spaces provided.

Spreadsheet

General Purpose Database Software

Boring Log Generator

Fence Diagram Generator

Laboratory Software

General Purpose X-Y Plot Software

General Purpose Contouring Software

Geographical Information System (GIS)

Image Analysis (remote sensing data)

Proprietary Instrumentation Software

Web-Based Imaging Systems

Other

2.16 **Who in your organization uses geotechnical data visualization software?** Check all that apply and enter other users in the space provided.

- ☐ Managers
- ☐ Planners and Designers
- ☐ Emergency Response Personnel
- ☐ Law Enforcement/Security

Survey Questionnaire

- [ ] Geologists
- [ ] Geotechnical Engineers
- [ ] Other Engineering Disciplines
- [ ] Laboratory Staff
- [ ] Maintenance Personnel
- [ ] Construction Personnel
- [ ] Other

SECTION 3. HAZARD MITIGATION TO AVERT DISASTER

3.01 **What types of geotechnical hazards have you been able to mitigate impacts through data collection and visualization?** Check all that apply and enter other types in the space provided.

- [ ] Landslides
- [ ] Embankment Failures
- [ ] Rock Falls
- [ ] Debris Flows
- [ ] Avalanches
- [ ] Slope Creep
- [ ] Wind Blown Soil / Dunes
- [ ] Settlement or Heave
- [ ] Lateral Spreading
- [ ] Surface Ruptures
- [ ] Subsidence
- [ ] Sinkholes
- [ ] Permafrost Thaw / Freeze
- [ ] Frozen Debris Lobes
- [ ] Other

3.02 **What types of geotechnical hazards have you been unable to successfully mitigate?** Check all that apply and enter other types in the space provided.

- [ ] Landslides
- [ ] Embankment Failures
- [ ] Rock Falls
- [ ] Debris Flows
- [ ] Avalanches
- [ ] Slope Creep
- [ ] Wind Blown Soil / Dunes
- [ ] Settlement or Heave
- [ ] Lateral Spreading
- [ ] Surface Ruptures
- [ ] Subsidence
- [ ] Sinkholes
- [ ] Frozen Debris Lobes
- [ ] Permafrost Thaw / Freeze
- [ ] Other

3.03 **In what phase of developing hazard mitigation measures do you use geotechnical data visualization?** Check all that apply and enter other uses in the space provided.

- [ ] Hazard Identification
- [ ] Condition Assessment
- [ ] Condition Monitoring
- [ ] Planning Mitigation
- [ ] Analysis of Mitigation
- [ ] Design of Mitigation
- [ ] Construction of Mitigation
- [ ] Other

Survey Questionnaire

3.04 **How has geotechnical data visualization contributed to the development of hazard mitigation measures?** Check all that apply and enter other responses in the space provided.

- ☐ Clearer Identification of Potential Issues
- ☐ Better Assessment of the Issue
- ☐ Better Monitoring
- ☐ Better Analysis
- ☐ Better Design
- ☐ Other

3.05 **How has geotechnical data visualization contributed to the implementation of hazard mitigation measures?** Check all that apply and enter other responses in the space provided.

- ☐ Improved Public Safety
- ☐ Improved Traffic Mobility
- ☐ Improved Worker Safety
- ☐ Better Analysis
- ☐ Faster Construction
- ☐ Other

SECTION 4. RESPONDING TO DISASTERS AND EXTREME EVENTS

4.01 **What geotechnical data would you find most useful in responding to disasters or extreme events?** Check all that apply and add additional responses in the space provided.

- ☐ Geologic Maps
- ☐ Boring / Well Logs
- ☐ Laboratory Test Results
- ☐ Groundwater Data
- ☐ Subsurface Profiles
- ☐ Geotechnical Reports
- ☐ Instrument Monitoring Reports
- ☐ Corridor Maps / Air Photos
- ☐ Design Drawings
- ☐ As-Built Drawings
- ☐ Construction Logs
- ☐ Maintenance Logs
- ☐ Extreme Event Reports
- ☐ Pre-Event Photos
- ☐ Data From Similar Sites
- ☐ Other

4.02 **What geotechnical data do you have on-line access to in the field when responding to disasters or extreme events?** Check all that apply and add additional responses in the space provided.

- ☐ Geologic Maps
- ☐ Boring / Well Logs
- ☐ Laboratory Test Results
- ☐ Groundwater Data
- ☐ Subsurface Profiles
- ☐ Geotechnical Reports
- ☐ Design Drawings
- ☐ As-Built Drawings
- ☐ Construction Logs
- ☐ Maintenance Logs
- ☐ Extreme Event Reports
- ☐ Pre-Event Photos

Survey Questionnaire

- [ ] Instrument Monitoring Reports
- [ ] Corridor Maps / Air Photos
- [ ] Data From Similar Sites
- [ ] Other

4.03 **Does geotechnical data visualization play a role in any of these aspects of your response to disasters or extreme events?** Check all that apply and add additional responses in the space provided.

- [ ] Damage Assessment
- [ ] Safety Analysis
- [ ] Communication and Coordination
- [ ] Public Safety
- [ ] Traffic Control and Routing
- [ ] Temporary Repair Design
- [ ] Temporary Repair Implementation
- [ ] Worker Safety
- [ ] Other

SECTION 5. LONG-TERM RECOVERY FROM DISASTERS AND EXTREME EVENTS

5.01 **What geotechnical data do you find most useful in long-term recovery from disasters or extreme events?** Check all that apply and add additional responses in the space provided.

- [ ] Geologic Maps
- [ ] Boring / Well Logs
- [ ] Laboratory Test Results
- [ ] Groundwater Data
- [ ] Subsurface Profiles
- [ ] Geotechnical Reports
- [ ] Corridor Maps / Air Photos
- [ ] Design Drawings
- [ ] As-Built Drawings
- [ ] Construction Logs
- [ ] Maintenance Logs
- [ ] Extreme Event Reports
- [ ] Pre-Event Photos
- [ ] Data From Other Sites
- [ ] Other

5.02 **How do you use geotechnical data for long-term recovery from disasters or extreme events?** Check all that apply and add additional responses in the space provided.

- [ ] Assessment
- [ ] Planning
- [ ] Analysis
- [ ] Design
- [ ] Construction
- [ ] Other

5.03 **In what way has geotechnical data visualization contributed to long-term recovery from disasters or extreme events?** Check all that apply and add additional responses in the space provided.

- [ ] Quicker Recovery
- [ ] Improved Public Safety
- [ ] Improved Traffic Mobility
- [ ] More Economic Design and Construction
- [ ] Improved Public / Stakeholder Communication
- [ ] Other

Survey Questionnaire

☐ Improved Worker Safety

SECTION 6. EVALUATION AND OPINION

6.01 **How often does your organization use tools to visualize geotechnical data for disaster or extreme event response and mitigation?**

○ Frequently ○ Occasionally ○ Rarely ○ Don't Use ○ Don't Know

6.02 **How would you characterize your organization's level of use of geotechnical data visualization tools?**

○ Expert Level ○ Intermediate Level ○ Entry Level ○ Don't Use

6.03 **Geotechnical data visualization improves our ability to mitigate hazards.** Indicate your level of agreement.

○ Agree ○ Generally Agree ○ Generally Disagree ○ Disagree ○ No Opinion

6.04 **Geotechnical data visualization improves our ability to respond to disasters or extreme events.** Indicate your level of agreement.

○ Agree ○ Generally Agree ○ Generally Disagree ○ Disagree ○ No Opinion

6.05 **Geotechnical data visualization improves our ability to achieve long-term recovery from disasters or extreme events.** Indicate your level of agreement.

○ Agree ○ Generally Agree ○ Generally Disagree ○ Disagree ○ No Opinion

6.06 **Please provide any additional comments you may have regarding geotechnical data visualization for disaster response and mitigation.**

Thank You!

Thank you for replying to this questionnaire. If you have any questions or comments, please feel free to contact Mr. Hollie Ellis at

Email: hle@shanwil.com
Phone: (206) 695-6847

APPENDIX B

Survey Response Matrices

1.01 What natural phenomena hazards do you encounter?

Hazard	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Earthquakes	X	X		X					X		X	X	X					X			X	X				X	X	X	X		X	X	X			X		X	X				20
Volcanoes	X																					X																					2
Floods	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	40
Tsunamis	X			X					X																						X		X										5
Extreme Precipitation	X	X		X	X	X		X	X	X			X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X		X	35
Extreme Temperatures	X	X			X					X				X					X	X	X	X		X		X	X	X	X			X			X		X	X	X	X		X	21
Freezing/Thawing Grour	X				X		X			X	X	X	X	X		X	X	X	X	X		X	X	X	X	X	X	X	X	X		X		X	X	X		X	X	X	X	X	31
High Velocity Winds	X	X			X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X		X	X	X	X		X		X				31
Storm Surges	X	X		X		X		X	X						X	X	X	X					X			X	X		X		X			X			X						17
Other			X													X	X						X						X														5
Count	9	6	1	5	5	4	3	4	6	4	3	4	5	5	3	6	6	6	5	5	5	7	6	4	4	7	6	6	8	4	5	6	5	5	5	3	5	5	6	4	2	4	

1.02 What geotechnical hazards do you encounter?

Hazard	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Landslides	X	X	X	X	X		X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	40
Embankment Failures	X	X	X	X	X	X		X		X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	39
Rock Falls	X	X	X	X	X	X		X	X	X	X		X	X		X	X	X		X		X	X			X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	34
Debris Flows	X			X	X				X		X			X			X					X	X	X				X	X	X	X		X					X	X			X	18
Extreme Precipitation	X				X						X											X						X			X							X				X	8
Slope Creep	X	X	X	X	X			X	X	X	X		X	X		X	X		X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	35
Wind Blown Soil/Dunes														X									X		X	X		X			X							X				X	8
High Velocity Winds	X	X	X		X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	39
Lateral Spreading	X		X	X							X							X	X	X		X	X	X				X	X		X		X		X			X	X		X		18
Surface Ruptures	X		X	X																		X						X	X				X					X					8
Subsidence	X	X	X		X			X		X	X	X	X	X	X		X	X	X	X	X	X	X				X	X	X	X		X	X			X		X	X		X		28
Sinkholes		X	X		X			X	X	X			X	X	X		X	X	X	X	X	X	X				X	X	X	X		X	X	X		X		X	X	X	X	X	29
Permafrost Thaw/Freeze	X																					X																					2
Frozen Debris Lobes	X																																										1
Other					X																		X						X														3
Count	12	7	9	7	10	3	2	7	6	7	9	3	7	9	4	4	8	7	7	8	6	12	11	6	5	4	7	12	11	8	9	7	10	5	6	7	4	12	9	6	8	9	

1.03 What geotechnical disasters have you had to respond to?

		AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Disaster	Landslides	X	X	X	X	X			X	X	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	37
	Embankment Failures	X	X	X	X	X	X		X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	39
	Rock Falls	X	X	X	X	X	X		X	X	X	X			X		X	X	X		X		X	X			X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	33
	Debris Flows				X	X				X		X			X			X					X		X				X	X		X		X					X	X			X	15
	Avalanches	X				X						X																	X										X					5
	Slope Creep		X	X	X				X	X	X			X	X		X	X		X	X		X	X	X				X	X		X	X	X		X			X	X		X		24
	Wind Blown Soil/Dunes														X														X			X							X					4
	Settlement or Heave	X	X	X				X	X	X	X	X			X		X	X	X	X	X		X	X	X	X	X	X	X	X		X	X	X	X	X		X	X	X	X	X	X	33
	Lateral Spreading	X		X	X							X							X	X				X	X				X	X				X		X				X		X		14
	Surface Ruptures	X		X	X																								X	X				X										6
	Subsidence	X	X	X					X		X	X	X	X	X			X	X	X	X	X		X				X	X	X	X		X	X			X			X		X		24
	Sinkholes		X	X		X			X	X	X			X	X	X		X	X	X	X	X	X	X				X	X	X	X		X	X			X		X	X	X	X	X	28
	Permafrost Thaw/Freeze	X																																										1
	Frozen Debris Lobes																																											0
	Other					X																	X	X				X		X														5
	Count	9	7	9	7	7	2	1	7	7	7	8	3	5	9	2	4	8	6	7	7	4	8	9	6	3	4	7	12	11	5	7	7	10	1	6	5	4	9	9	5	8	6	

2.01 What geotechnical data does your organization keep on paper file?

		AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Type	Geologic Maps		X	X	X			X	X	X	X	X		X			X	X		X	X	X	X	X	X	X		X	X	X		X	X	X		X	X		X	X	X	X	X	31
	Boring / Well Logs		X	X	X	X		X		X	X	X		X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X		X	X	X		X	X		X	X	X		X	33
	Groundwater Data		X		X	X		X			X	X			X			X	X		X		X	X	X		X	X	X	X		X				X							X	20
	Subsurface Profiles		X		X			X			X	X			X	X	X	X	X		X	X		X	X	X		X	X	X		X	X	X		X	X		X				X	25
	Geotechnical Reports		X	X	X	X		X	X	X	X	X			X		X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X		X	X	X		X	34
	Instrument Monitoring Re		X								X	X			X		X	X			X	X	X	X		X	X		X	X		X	X	X		X	X		X		X		X	22
	Corridor Maps / Air Photo				X	X					X	X				X		X	X		X		X	X		X			X	X		X		X		X	X						X	18
	Design Drawings		X			X					X	X	X		X	X	X		X		X	X	X	X	X	X		X	X	X		X	X	X		X	X		X			X	X	26
	As-Built Drawings		X	X	X	X			X	X	X	X	X		X	X		X			X		X	X		X	X	X	X	X		X	X	X		X			X				X	26
	Construction Logs				X	X					X	X			X	X					X		X	X	X	X	X	X	X			X		X	X				X					18
	Maintenance Logs		X							X	X	X									X			X		X			X			X		X	X									11
	Extreme Event Reports		X			X				X	X											X		X					X				X	X					X					10
	Pre-Event Photos		X			X																X	X														X						X	6
	Data From Other Sites										X																																	1
	Other				X		X																	X						X														4
	Count*	0	11	4	9	9	1	5	3	6	13	11	2	2	8	6	6	8	6	2	11	8	10	13	7	10	6	8	12	10	0	11	8	11	3	9	8	0	9	3	4	2	10	

* Count = 0 may imply no response to this question

2.02 What geotechnical data does your organization keep in electronic format suitable for visualization?

Item	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Geologic Maps		X		X			X	X		X			X		X		X	X		X					X	X	X		X	X		X	X	X		X		X	X		X	X	23
Boring / Well Logs		X		X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X		X		X	X	X	X	X	35
Laboratory Test Results				X	X	X	X			X	X		X	X	X		X	X	X	X	X	X	X	X	X	X	X	X		X		X			X	X		X	X		X	X	29
Groundwater Data				X			X			X			X	X				X	X	X		X	X		X	X	X	X		X		X		X				X			X	X	20
Subsurface Profiles		X		X		X	X			X	X	X	X	X	X			X					X			X				X	X			X	X			X		X	X	X	21
Geotechnical Reports		X	X	X	X	X	X			X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X		X			X		X	X		X	X	X	X	X	33
Instrument Monitoring Re		X	X		X					X	X		X		X								X			X	X			X	X				X	X		X	X	X	X	X	19
Corridor Maps / Air Photo		X			X					X			X		X				X				X		X	X	X	X				X	X			X			X		X	X	17
Design Drawings		X	X		X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X		X			X	X	X	X		X	X		X	X	31
As-Built Drawings			X	X	X			X	X	X	X		X	X	X		X		X	X		X	X		X	X		X										X	X		X	X	22
Construction Logs		X								X		X	X	X	X				X				X		X	X		X										X	X				13
Maintenance Logs		X								X													X		X														X				5
Extreme Event Reports		X								X											X		X											X				X					6
Pre-Event Photos					X																X					X				X				X		X						X	7
Data From Other Sites										X					X				X																								3
Other																X	X						X									X											4
Count*	0	10	4	7	8	5	6	2	1	14	7	5	11	8	11	3	7	7	9	7	6	6	13	4	10	11	8	8	2	9	3	6	4	7	5	8	0	11	10	4	10	11	

* Count = 0 may imply no response to this question

2.03 Does your organization have a centralized electronic database for any or all of the geotechnical data listed in Question 2.02?

Reply	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Yes	X				X		X				X	X				X	X		X			X		X		X		X			X		X	X	X		X	X			X		19
No		X	X	X		X		X	X	X			X	X	X			X		X	X		X		X		X		X	X		X				X			X	X		X	23
Count*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	

2.04 If yes to question 2.03, how long is the data retained?

Reply	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Permanently		X		X		X			X	X			X	X	X					X	X				X				X	X		X				X			X	X		X	18
Don't Know			X					X									X																										3
Other																X		X					X				X																4
Count*	0	1	1	1	0	1	0	1	1	1	0	0	1	1	1	1	1	1	0	1	1	0	1	0	1	0	1	0	1	1	0	1	0	0	0	1	0	0	1	1	0	1	

* Count = 0 may imply no response to this question

2.05 If yes to question 2.03, what database do you use?

Reply	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Department Developed Da		X	X	X		X		X		X			X	X			X						X		X		X			X						X			X				15
Commercial Database									X						X			X		X	X								X			X								X		X	9
Count*	0	1	1	1	0	1	0	1	1	1	0	0	1	1	1	0	1	1	0	1	1	0	1	0	1	0	1	0	1	1	0	1	0	0	0	1	0	0	1	1	0	1	

* Count = 0 may imply no response to this question

2.07 What geotechnical instrumentation does your organization use?

Type	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Open Stand Pipe Wells		X	X	X	X	X		X	X		X		X					X	X	X	X	X	X	X	X		X	X	X	X	X		X		X	X		X	X	X		X	29
Piezometers		X	X	X	X	X			X	X	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X		X	X	X	X	X	35
Inclinometers		X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X		X	X	X	X	X	38
Settlement Gages		X		X	X	X			X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X			X			X	X	X	X	X	33
Displacement Gages			X		X			X			X			X	X				X	X		X					X											X					11
Load Gages		X		X	X				X	X	X			X						X			X				X			X	X	X						X	X				15
Extensometers			X		X						X		X	X			X		X	X		X	X	X		X	X		X	X	X	X			X			X					19
Plumblines											X								X				X		X		X					X											6
Liquid Level Systems					X			X			X			X									X	X											X								7
Optical Surveys		X	X	X	X				X		X			X		X	X	X	X	X		X	X	X	X	X	X	X	X		X	X						X		X			24
Total Station Survey Syste					X						X			X			X		X	X	X	X	X		X	X		X					X					X			X		15
Seismometers					X						X		X						X				X						X									X					7
Other					X						X					X			X				X											X		X			X				8
Count	0	6	6	6	12	4	0	4	6	4	13	3	6	9	4	4	6	5	9	9	5	8	12	7	7	6	9	6	7	6	7	7	4	1	6	4	0	10	6	5	4	4	

* Count = 0 may imply no response to this question

2.08 On what types of projects do you use geotechnical instrumentation?

		AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Project	During New Construction		X	X		X	X	X		X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X		X	36
	Long Term, Post-Constru		X		X	X	X			X	X	X		X	X	X		X			X	X	X	X		X	X	X		X	X		X	X		X	X		X	X	X		X	28
	Hazard Monitoring		X	X	X	X		X	X	X		X	X	X	X	X		X		X	X	X	X	X	X	X			X	X	X	X	X	X		X	X		X	X		X	X	32
	Foundations, Subgrade		X			X		X			X	X		X	X	X		X		X		X	X	X	X	X		X	X				X		X	X				X		X		22
	Pavement							X			X	X		X	X					X						X							X		X									9
	Bridges		X	X		X		X	X	X	X	X		X	X	X				X			X	X	X	X		X		X	X		X		X		X		X	X		X		25
	Other				X			X									X							X									X											5
	Count	0	5	3	3	5	2	6	2	4	5	6	2	6	6	5	1	4	1	5	3	4	5	6	4	6	2	4	3	4	4	2	7	3	4	4	4	0	4	5	2	3	3	

* Count = 0 may imply no response to this question

2.09 How is the decision to use geotechnical instrumentation made?

		AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Method	Required by Department							X				X				X												X					X	X										6
	Risk Analysis								X		X				X				X			X	X	X		X	X	X			X					X								12
	Expert Opinion and Engine		X	X	X	X	X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	37
	Other				X														X												X													3
	Count	0	1	1	2	1	1	1	1	1	2	2	1	1	2	2	1	1	2	1	1	2	2	2	1	2	2	3	1	1	3	1	2	2	1	2	1	0	1	1	1	1	1	

* Count = 0 may imply no response to this question

2.10 How do you collect geotechnical instrumentation data?

		AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Method	Manual Readings			X	X	X	X			X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	36
	Automated Data Acquisitic				X	X	X				X	X		X		X		X		X	X		X	X	X			X		X	X	X	X	X	X		X		X	X	X		X	25
	Portable Electronic Device		X	X	X	X			X	X	X	X		X	X	X		X	X		X	X	X	X	X	X		X	X		X				X	X	X		X		X	X		28
	Other																X																		X									2
	Count	0	1	2	3	3	2	0	1	2	3	3	1	3	2	3	1	3	2	2	3	2	3	3	3	2	1	3	2	2	3	2	2	2	4	2	3	0	3	2	3	2	2	

* Count = 0 may imply no response to this question

2.11 How do you establish hazard mitigation warning and action levels for geotechnical instrumentation data?

Method	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Field Tests							X	X		X	X				X		X			X	X				X		X	X				X	X	X	X			X					16
Laboratory Tests			X				X	X			X						X			X	X				X	X		X				X	X		X				X				14
Analysis			X		X			X		X	X	X		X			X			X	X	X	X		X	X	X	X		X		X	X	X	X	X		X	X	X	X	X	27
Expert Opinion and Engine		X	X	X	X	X		X	X	X	X		X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X		X	X	X	X	X	36
Other																		X									X				X												3
Count	0	1	3	1	2	1	2	4	1	3	4	1	1	2	2	1	4	1	1	4	4	2	2	1	4	3	4	4	1	2	1	4	4	3	4	2	0	3	3	2	2	2	

* Count = 0 may imply no response to this question

2.12 How do you store and process geotechnical instrumentation data?

Method	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Spreadsheets		X		X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X		X	X		X	X	X	X	X	36
Department's Central Data				X		X				X											X		X									X		X								X	8
Vendor Software and Data		X	X								X		X		X		X		X	X	X	X		X	X			X		X	X	X	X		X	X				X	X		21
Web-Based Software and					X														X																				X			X	4
Other					X								X			X			X																X				X				6
Count	0	2	1	2	3	2	1	1	1	2	2	1	3	1	2	1	2	1	4	2	2	2	2	2	2	1	1	2	1	2	2	3	2	1	3	2	0	1	3	2	2	3	

* Count = 0 may imply no response to this question

2.13 What remote sensing data does your organization use for geotechnical mapping and monitoring?

Project	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Air Photos		X		X	X	X	X			X	X	X	X		X				X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X		X	X		X	X	31
Satellite Images		X		X						X	X	X	X		X	X	X			X	X	X	X		X	X	X	X	X				X			X					X	X	22
LIDAR		X	X	X	X					X	X	X		X	X	X	X		X	X	X	X	X		X			X	X	X	X	X				X			X		X	X	26
Topographic Data			X	X		X				X	X	X	X		X	X			X	X	X	X	X	X				X	X	X	X			X	X	X			X	X	X	X	26
Radar (SAR, inSAR, GPR, et				X	X					X	X								X			X	X											X						X		X	10
Thematic Data (e.g. soil ty						X					X		X																		X												4
Other								X	X							X							X																				4
Count	0	3	2	5	3	3	1	1	1	5	6	4	4	1	4	4	2	0	4	4	4	5	6	2	3	2	2	4	4	3	4	2	1	3	2	4	0	1	3	2	4	5	

* Count = 0 may imply no response to this question

2.14 Where do you obtain remote sensing data for geotechnical mapping and monitoring?

		AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Source	Commercial Sources		X			X	X									X	X												X								X					X		8
Source	USGS			X	X		X				X			X			X	X		X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X				X	X		25
Source	USDA						X				X			X						X	X	X								X		X				X						X		10
Source	Google or Bing Maps		X	X			X				X		X	X		X	X	X		X	X	X	X	X			X		X	X	X		X			X	X		X				X	23
Source	Google Earth		X		X		X	X			X		X				X	X		X	X	X	X	X	X	X	X		X	X			X	X	X	X	X		X	X	X	X	X	28
Source	COSMOS																																											0
Source	NASA				X																																							1
Source	Generated by Department		X	X		X	X				X		X	X		X				X		X	X	X	X	X	X		X	X	X	X	X		X	X	X			X	X		X	26
Source	Other				X				X	X				X				X																										5
	Count	0	4	3	4	2	6	1	1	1	5	0	3	5	0	3	4	4	0	5	4	5	4	4	3	3	4	1	5	5	3	3	3	1	3	5	5	0	2	2	3	4	3	

* Count = 0 may imply no response to this question

2.15 What geotechnical data visualization software does your organization use?

		AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Type	Spreadsheet		X	X	X	X	X		X	X	X		X	X	X	X			X	X		X	X	X	X	X	X		X		X	X		X			X		X		X	X	X	29
Type	General Purpose Databas		X	X			X							X		X				X	X			X	X						X	X	X				X		X	X	X	X	X	18
Type	Boring Log Generator		X	X	X	X	X				X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X		X		X	X	X		X		X		X	X	X	X	X	32
Type	Fence Diagram Generator											X	X	X		X		X			X	X	X				X				X	X	X				X				X	X	X	16
Type	Laboratory Software			X		X	X				X	X		X		X		X	X	X	X	X	X	X	X	X	X		X		X	X	X				X		X		X			24
Type	General Purpose X-Y Plot		X								X			X		X			X		X	X	X	X		X	X					X					X				X	X		15
Type	General Purpose Contour		X			X					X			X		X			X	X				X		X					X	X					X			X	X	X	X	16
Type	Geographical Information		X			X	X		X		X			X		X					X	X		X	X	X	X				X	X				X	X				X	X		19
Type	Image Analysis (remote s					X					X			X		X										X						X					X				X		X	9
Type	Proprietary Instrumentati		X	X		X								X		X			X	X				X	X	X					X	X					X		X		X		X	16
Type	Web-Based Imaging Syste					X								X										X		X						X				X	X				X			8
Type	Other																			X																				X			X	3
	Count	0	7	5	2	8	5	0	2	1	7	3	3	11	2	10	0	3	6	6	6	6	5	9	6	9	6	0	3	0	8	11	4	1	1	2	11	0	5	3	11	7	7	

* Count = 0 may imply no response to this question

2.16 Who in your organization uses geotechnical data visualization software?

Type	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN
Managers					X														X	
Planners and Designers					X					X			X				X		X	
Geologists		X	X	X	X			X		X	X		X	X			X			X
Geotechnical Engineers		X	X	X	X	X		X	X	X	X	X	X	X	X		X	X	X	X
Other Engineering Discipli				X						X										
Laboratory Staff					X					X					X				X	
Emergency Response Per					X															
Law Enforcement/Security																				
Maintenance Personnel										X										
Construction Personnel										X										
Other																				
Count	0	2	2	3	6	1	0	2	1	7	2	1	3	2	2	0	3	1	4	2

Type	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Managers			X		X	X		X		X						X						X	9
Planners and Designers	X							X		X		X											9
Geologists	X	X	X		X			X		X	X	X	X		X	X		X	X	X	X	X	27
Geotechnical Engineers	X	X	X	X	X	X		X		X	X	X	X		X	X		X	X	X	X	X	35
Other Engineering Discipli				X		X		X		X										X			7
Laboratory Staff	X		X		X			X		X													9
Emergency Response Per																							1
Law Enforcement/Security																							0
Maintenance Personnel	X									X						X							4
Construction Personnel										X		X				X							4
Other	X									X													2
Count	6	2	4	2	4	3	0	6	0	9	2	4	2	0	2	5	0	2	2	3	2	3	

* Count = 0 may imply no response to this question

3.01 What types of geotechnical hazards have you been able to mitigate impacts through data collection and visualization?

Hazard	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN
Landslides		X	X	X	X		X		X	X	X	X	X						X	X
Embankment Failures			X	X	X	X			X	X	X		X		X		X	X	X	X
Rock Falls			X	X	X				X	X	X						X			
Debris Flows				X							X									
Avalanches											X									
Slope Creep		X	X							X	X		X						X	
Wind Blown Soil / Dunes																				
Settlement or Heave			X			X	X			X	X				X			X	X	X
Lateral Spreading			X															X	X	
Surface Ruptures																				
Subsidence										X		X					X	X	X	
Sinkholes		X							X	X					X		X		X	X
Permafrost Thaw / Freeze																				
Frozen Debris Lobes																				
Other								X												
Count	0	3	6	4	3	2	2	1	4	7	7	2	3	0	3	0	4	4	7	4

Hazard	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Landslides	X	X	X	X	X			X		X	X	X	X		X	X		X	X	X	X	X	29
Embankment Failures		X	X	X	X		X	X		X	X	X	X	X	X	X		X		X	X	X	30
Rock Falls		X				X	X	X		X	X	X	X		X	X		X	X	X	X	X	22
Debris Flows				X									X									X	5
Avalanches																							1
Slope Creep			X									X	X								X	X	11
Wind Blown Soil / Dunes																							0
Settlement or Heave		X	X	X	X					X		X	X	X				X		X	X	X	21
Lateral Spreading			X										X								X		6
Surface Ruptures													X										1
Subsidence	X						X			X		X	X			X					X		12
Sinkholes	X		X				X			X		X	X			X					X	X	16
Permafrost Thaw / Freeze																							0
Frozen Debris Lobes																							0
Other			X						X														3
Count	3	4	7	4	3	1	4	3	1	6	3	7	10	2	3	5	0	4	2	4	8	7	

3.02 What types of geotechnical hazards have you been unable to successfully mitigate?

		AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Hazard	Landslides			X	X			X									X						X		X						X									X			X	9
	Embankment Failures			X	X					X								X					X		X						X				X					X			X	10
	Rock Falls			X	X					X							X	X					X	X							X												X	9
	Debris Flows				X	X																	X	X					X					X					X				X	8
	Avalanches																												X										X					2
	Slope Creep		X	X	X												X									X			X										X					7
	Wind Blown Soil / Dunes																												X			X							X					3
	Settlement or Heave			X				X									X						X						X		X				X									7
	Lateral Spreading			X																									X										X					3
	Surface Ruptures			X																									X										X					3
	Subsidence													X										X					X		X								X	X				6
	Sinkholes			X		X								X				X					X						X		X			X	X				X	X	X			12
	Frozen Debris Lobes																																						X					1
	Permafrost Thaw / Freeze																																						X					1
	Other								X															X									X											3
	Count	0	1	8	5	2	0	2	1	2	0	0	0	2	0	0	4	3	0	0	0	0	6	4	2	1	0	0	9	0	6	1	1	2	3	0	0	0	10	4	1	0	4	

3.03 In what phase of developing hazard mitigation measures do you use geotechnical data visualization?

		AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Phase	Hazard Identification			X	X						X	X	X	X		X		X		X	X	X	X	X		X	X		X		X	X	X		X	X	X		X	X			X	25
	Condition Assessment			X	X	X				X	X	X	X	X		X		X		X	X	X	X	X		X	X	X	X	X	X	X	X			X	X		X	X	X	X	X	30
	Condition Monitoring		X	X	X	X	X				X	X		X		X		X		X	X	X	X	X	X	X	X		X	X	X	X	X				X		X	X	X	X	X	29
	Planning Mitigation		X	X							X	X				X		X		X	X		X	X	X	X		X	X		X	X	X				X			X	X	X		21
	Analysis of Mitigation			X		X				X	X	X	X	X		X	X	X		X	X		X	X	X	X	X		X		X	X	X	X			X		X	X	X	X	X	28
	Design of Mitigation		X	X	X	X				X	X	X		X		X	X	X		X	X	X	X	X	X	X	X		X		X	X	X	X			X		X	X	X	X	X	30
	Construction of Mitigation		X			X	X				X	X		X			X	X		X	X		X	X	X	X	X	X	X		X	X	X	X			X		X		X		X	25
	Other					X			X										X																									3
	Count	0	4	6	4	6	2	0	1	3	7	7	3	6	0	6	3	7	1	7	7	4	7	7	5	7	6	3	7	2	7	7	7	3	1	2	7	0	6	6	6	5	6	

3.04 How has geotechnical data visualization contributed to the development of hazard mitigation measures?

Outcome	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Clearer Identification of P			X	X	X				X	X	X		X				X		X	X	X	X	X		X	X	X	X		X	X	X		X	X	X		X	X		X	X	27
Better Assessment of the		X	X	X	X				X	X	X		X				X		X	X	X	X	X		X	X	X	X	X	X	X	X	X		X	X		X	X	X	X	X	30
Better Monitoring			X	X	X		X			X					X		X		X	X		X	X	X	X		X			X	X	X				X		X	X	X		X	22
Better Analysis		X	X		X				X	X	X		X		X		X		X		X	X	X		X		X			X	X		X		X	X		X		X	X	X	24
Better Design		X	X	X	X				X	X	X		X		X		X	X	X		X	X	X		X	X	X			X	X	X				X		X		X	X	X	26
Other			X					X																																			2
Count	0	3	6	4	5	0	1	1	4	5	4	0	4	0	3	0	5	1	5	3	4	5	5	1	5	3	5	2	1	5	5	4	2	1	3	5	0	5	3	4	4	5	

3.05 How has geotechnical data visualization contributed to the implementation of hazard mitigation measures?

Outcome	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Improved Public Safety			X	X	X		X		X		X	X	X		X		X	X	X	X	X	X	X		X	X	X	X		X	X	X	X	X	X	X		X	X		X	X	31
Improved Traffic Mobility			X	X					X		X						X		X						X		X			X	X							X	X	X		X	14
Improved Worker Safety			X	X	X						X						X		X		X	X	X		X	X	X					X				X					X	X	16
Better Analysis		X	X	X	X				X	X	X	X	X		X		X		X	X	X	X		X	X	X	X			X	X	X				X		X		X	X	X	27
Faster Construction		X		X						X							X					X			X			X								X							8
Other			X					X															X																				3
Count	0	2	5	5	3	0	1	1	3	2	4	2	2	0	2	0	5	1	4	2	3	4	3	1	5	3	4	2	0	3	3	3	1	1	1	4	0	3	2	2	3	4	

4.01 What geotechnical data would you find most useful in responding to disasters or extreme events?

Item	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Geologic Maps		X	X	X	X	X	X	X	X	X	X					X	X	X		X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X		X		X	32
Boring / Well Logs		X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X		X	X			X		X	X	X	35
Laboratory Test Results			X	X		X	X	X		X	X			X		X	X	X		X		X	X	X	X	X		X	X			X						X		X	X	X	24
Groundwater Data		X	X	X	X	X	X	X	X	X	X		X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X		X			X		X	X	X	33
Subsurface Profiles		X	X	X	X	X		X		X	X		X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X		X		X	X			X		X	X	X	32
Geotechnical Reports		X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X		X	X		X	X	X		X		X	X	X	35
Instrument Monitoring Re		X	X		X	X		X		X	X				X		X	X	X	X		X	X	X	X	X	X	X	X	X		X	X		X			X		X	X	X	28
Corridor Maps / Air Photo		X	X	X	X	X		X		X						X	X				X	X	X	X		X		X	X	X		X	X			X		X				X	22
Design Drawings			X			X		X		X		X			X	X	X			X	X	X	X	X		X		X	X			X			X	X		X		X		X	22
As-Built Drawings			X	X	X	X		X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X		X				X	X	X	X	X	33
Construction Logs			X			X		X		X	X				X	X	X	X				X	X		X	X		X				X		X				X				X	18
Maintenance Logs		X	X		X	X		X		X					X	X	X					X	X		X	X		X				X	X	X				X				X	19
Extreme Event Reports		X	X		X	X		X		X						X	X					X	X	X	X	X	X	X				X	X	X				X				X	20
Pre-Event Photos		X	X		X	X		X		X			X			X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X		X	X	29
Data From Similar Sites			X		X					X						X	X					X	X			X		X				X	X					X				X	13
Other																	X		X													X											3
Count*	0	10	15	8	12	14	4	14	5	15	9	3	6	4	8	14	16	9	6	9	8	15	15	11	11	15	9	15	11	8	4	16	8	9	8	5	0	15	2	9	8	15	

* Count = 0 may imply no response to this question

4.02 What geotechnical data do you have on-line access to in the field when responding to disasters or extreme events?

Item	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Geologic Maps				X			X	X					X								X	X		X						X						X		X	X			X	12
Boring / Well Logs			X	X			X								X				X			X	X					X		X		X		X		X			X			X	14
Laboratory Test Results							X								X				X			X	X					X		X		X				X						X	10
Groundwater Data							X												X			X	X					X		X												X	7
Subsurface Profiles															X								X							X				X									4
Geotechnical Reports			X	X															X		X	X	X					X				X				X			X			X	11
Instrument Monitoring Re			X		X										X				X			X																				X	6
Corridor Maps / Air Photo		X	X																											X	X					X			X			X	7
Design Drawings																					X		X									X				X		X					5
As-Built Drawings				X											X				X																				X			X	5
Construction Logs																																											0
Maintenance Logs															X																												1
Extreme Event Reports																																		X									1
Pre-Event Photos			X																											X	X			X								X	5
Data From Similar Sites															X																												1
Other																			X								X		X			X				X							5
Count*	0	1	5	4	1	0	4	1	0	0	0	0	1	0	7	0	0	0	7	0	3	6	6	1	0	0	1	4	1	7	2	5	0	4	0	7	0	2	5	0	0	9	

* Count = 0 may imply no response to this question

4.03 Does geotechnical data visualization play a role in any of these aspects of your response to disasters or extreme events?

Item	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Damage Assessment			X	X	X				X	X	X						X		X		X			X	X	X	X	X	X	X		X	X			X		X	X	X	X	X	24
Safety Analysis		X	X	X	X		X			X	X		X		X				X		X		X		X	X		X		X		X				X		X	X	X	X	X	23
Communication and Coor			X							X					X		X					X			X	X		X				X			X	X				X			12
Public Safety			X	X	X		X				X				X				X		X		X		X	X	X	X				X				X		X		X	X	X	19
Traffic Control and Routin			X	X	X																		X		X	X		X				X				X							9
Temporary Repair Design		X	X	X	X				X	X	X		X			X	X	X	X		X	X	X		X	X	X	X	X	X	X	X				X		X		X	X	X	28
Temporary Repair Implem			X	X	X				X	X	X		X			X	X		X		X	X	X		X	X		X			X	X				X		X				X	21
Worker Safety			X	X	X		X			X			X						X		X	X	X		X		X	X				X				X				X		X	17
Other						X		X																																			2
Count*	0	2	8	7	7	1	3	1	3	6	5	0	4	0	3	2	4	1	6	0	6	4	6	1	8	7	4	8	2	3	2	8	1	0	1	8	0	5	2	6	4	6	

* Count = 0 may imply no response to this question

5.01 What geotechnical data do you find most useful in long-term recovery from disasters or extreme events?

Item	AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Geologic Maps			X	X			X			X	X						X	X	X					X	X		X	X	X						X	X			X				16
Boring / Well Logs			X	X	X		X	X	X	X	X	X	X	X	X		X	X	X			X	X	X	X	X			X			X	X	X		X			X	X	X		28
Laboratory Test Results			X	X	X		X	X	X	X	X		X	X	X		X	X				X			X		X		X			X	X						X	X	X		22
Groundwater Data			X	X	X		X	X	X	X	X		X				X	X	X			X			X	X	X		X			X	X		X				X	X	X		23
Subsurface Profiles			X	X			X	X		X			X	X	X		X	X				X	X	X	X	X	X		X			X		X						X	X	X	22
Geotechnical Reports		X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X				X	X		X			X	X	X	X	31
Corridor Maps / Air Photo		X	X	X	X					X							X					X			X		X	X	X						X	X			X			X	15
Design Drawings			X					X		X	X	X	X		X		X						X	X					X							X			X	X		X	15
As-Built Drawings		X	X	X				X	X	X	X	X	X	X	X	X	X	X	X		X		X		X	X	X	X	X			X		X					X	X			26
Construction Logs			X					X		X	X	X			X	X	X	X							X	X								X						X			13
Maintenance Logs		X	X		X			X		X					X	X	X				X			X		X					X			X						X			14
Extreme Event Reports		X	X		X			X		X						X	X				X		X	X	X	X	X					X								X			15
Pre-Event Photos				X	X			X		X						X	X							X	X	X	X		X							X			X				13
Data From Other Sites										X					X		X		X																								4
Other																	X		X													X											3
Count*	0	5	12	9	8	0	5	11	5	14	8	5	7	5	9	6	15	8	7	0	3	6	6	8	11	9	9	4	10	0	1	7	4	6	3	6	0	0	9	10	5	4	

* Count = 0 may imply no response to this question

5.02 How do you use geotechnical data for long-term recovery from disasters or extreme events?

		AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Phase	Assessment			X	X	X					X	X				X		X		X		X	X			X	X	X			X	X	X	X	X		X		X	X	X	X	X	24
	Planning		X	X	X	X					X	X	X			X		X		X		X	X		X	X		X			X		X	X	X		X			X	X	X	X	24
	Analysis		X	X	X	X				X	X	X	X	X		X				X			X	X	X	X	X	X	X		X	X	X	X	X		X			X	X	X	X	28
	Design		X	X	X	X				X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	35
	Construction		X	X	X						X	X		X	X	X	X			X			X	X		X	X	X	X	X		X	X	X			X			X	X	X	X	25
	Other								X																						X													2
	Count*	0	4	5	5	4	0	0	1	2	5	5	3	3	2	5	2	3	1	5	0	3	5	3	3	5	4	5	3	2	5	4	5	5	4	1	5	0	1	5	5	5	5	

* Count = 0 may imply no response to this question

5.03 In what way has geotechnical data visualization contributed to long-term recovery from disasters or extreme events?

		AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Item	Quicker Recovery		X	X	X						X	X	X			X		X	X			X	X	X		X			X		X			X			X		X	X	X	X	X	22
	Improved Public Safety			X	X	X		X		X		X	X	X		X		X		X		X	X	X		X	X	X	X		X				X		X		X		X	X		24
	Improved Traffic Mobility			X	X													X		X				X			X										X		X		X		X	10
	Improved Worker Safety			X	X	X		X			X					X		X		X		X	X	X		X											X				X	X		15
	More Economic Design an		X	X	X	X				X	X	X		X		X		X		X		X	X	X	X		X	X	X	X	X	X				X	X		X	X		X		26
	Improved Public / Stakehc			X	X	X												X						X		X	X					X					X					X		10
	Other			X					X																																			2
	Count*	0	2	7	6	4	0	2	1	2	3	3	2	2	0	4	0	6	1	4	0	4	4	6	1	4	4	2	3	1	3	2	0	1	1	1	6	0	4	2	4	5	2	

* Count = 0 may imply no response to this question

6.01 How often does your organization use tools to visualize geotechnical data for disaster or extreme event response and mitigation?

		AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Frequency	Frequently			X	X			X			X							X			X								X					X			X		X			X		11
Frequency	Occasionally		X									X				X				X		X	X	X		X	X	X			X		X							X	X		X	15
Frequency	Rarely					X	X		X	X			X	X					X						X					X		X			X	X								12
Frequency	Don't Use														X																													1
Frequency	Don't Know																X																											1
	Count*	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	

* Count = 0 may imply no response to this question

6.02 How would you characterize your organization's level of use of geotechnical data visualization tools?

		AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Level	Expert Level							X																		X					X											X		4
Level	Intermediate Level		X		X		X				X					X		X	X		X	X		X				X	X								X						X	14
Level	Entry Level			X		X			X	X		X	X	X	X					X			X		X		X			X		X	X	X	X	X			X	X	X			21
Level	Don't Use																X																											1
	Count*	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	

* Count = 0 may imply no response to this question

6.03 *Geotechnical data visualization improves our ability to mitigate hazards. Indicate your level of agreement.*

Level		AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Level	Agree			X	X	X		X			X	X		X		X	X	X					X	X		X	X				X	X	X				X		X			X		20
	Generally Agree		X						X	X									X	X	X	X			X			X	X					X	X	X				X	X		X	16
	Generally Disagree												X																	X														2
	Disagree																																											0
	No Opinion						X								X																													2
	Count*	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	

* Count = 0 may imply no response to this question

6.04 *Geotechnical data visualization improves our ability to respond to disasters or extreme events. Indicate your level of agreement.*

Level		AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Level	Agree			X	X	X	X	X		X	X	X		X		X	X	X	X				X	X		X	X	X			X		X				X		X			X		23
	Generally Agree		X						X				X							X	X	X			X							X		X	X	X				X	X		X	14
	Generally Disagree																													X														1
	Disagree																																											0
	No Opinion														X														X															2
	Count*	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	

* Count = 0 may imply no response to this question

6.05 *Geotechnical data visualization improves our ability to achieve long-term recovery from disasters or extreme events. Indicate your level of agreement.*

Level		AK	AL	AZ	CA	CO	CT	DE	GA	HI	IA	ID	IL	IN	KS	LA	MA	MD	ME	MI	MN	MO	MT	NC	ND	NE	NH	NJ	NV	NY	OH	OR	PA	PR	RI	SD	TN	TX	UT	VT	WI	WV	WY	Count
Level	Agree			X	X	X					X	X	X	X		X	X	X	X				X	X		X	X				X		X				X		X		X	X		21
	Generally Agree		X				X	X	X	X										X	X	X			X			X						X	X	X				X			X	15
	Generally Disagree																													X														1
	Disagree																																											0
	No Opinion														X														X															2
	Count*	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	

* Count = 0 may imply no response to this question

APPENDIX C

Survey Response Commentary

Approximately 80% of the state geotechnical leaders and others who received the study questionnaire responded. Their responses and commentary are presented here.

SECTION 1. HAZARDS, DISASTERS, AND EXTREME EVENTS

1.01 What natural phenomena hazards do you encounter?

The natural phenomena hazards encountered in each state depend, of course, on the state's geological and meteorological setting. Although earthquakes are a common geological hazard in about 50% of the states, meteorological impacts dominate the natural hazards. Nearly 90% of all natural hazards identified are weather-related. The typical transportation system geotechnical leader encounters four to six different natural phenomena hazards (Figure C1).

1.02 What geotechnical hazards do you encounter?

The geotechnical hazards identified by the geotechnical leaders generally reflect the geological and meteorological setting of their regions. However, four of the five most frequently identified geotechnical hazards are related to slope or embankment stability; the fifth is settlement or heave. This implies that geotechnical issues with natural or cut slopes and embankments or fills are nearly universal across all geological and meteorological regions. The most frequently mentioned "Other" item was bridge and roadway scour. The DOTs in each state typically encounter six to seven different types of geotechnical hazards (Figure C2).

1.03 What geotechnical disasters have you had to respond to?

Questions 1.02 and 1.03 each have 574 possible responses (41 respondents times 14 hazard types). Of these 574, 301 hazards were identified and, according to respondents, approximately 85% of the disasters had occurred. This implies that in 15% of the cases, the DOTs have identified the hazard, but have either mitigated the potential hazard or have not yet experienced the disaster of that type (Figure C3).

1.04 Which hazard, disaster, or extreme event types do you most frequently encounter?

The most frequently encountered hazards, disasters, and extreme events reported by the DOTs are generally consistent with the hazards and disasters most frequently identified in questions 1.02 and 1.03. More than half of the respondents reported that landslides were their most frequently encountered hazard or disaster. About one-third of the respondents reported embankment failures and rockfalls as being most frequent. On average, the DOTs identified one to two hazard or disaster types as being the most frequently encountered (Figure C4a).

1.05 Which hazard, disaster, or extreme event types are most detrimental to your organization's finances and reputation?

The hazards, disasters and extreme events most frequently reported as detrimental to the organization's finances and reputation are landslides and sinkholes. However, one respondent noted that, "Failures of constructed embankments are very expensive to correct and because they were engineered structures it reflects very poorly on the department when they fail." On average, the DOTs identified one or two hazard or disaster types as being the most detrimental to the organization's finances and reputation (Figure C4b).

SECTION 2. GEOTECHNICAL DATA MANAGEMENT

2.01 What geotechnical data does your organization keep on paper file?

The most common geotechnical data kept as paper files include logs, reports, maps, drawings, and other typical information that might be obtained from a hazard mitigation or disaster recovery project. Some information that might be useful in disaster response, such as extreme event reports or pre-event photographs, appears to be less commonly kept on file. On average, the DOTs keep about seven different types of geotechnical data in paper format (Figure C5).

2.02 What geotechnical data does your organization keep in electronic format suitable for visualization?

The distribution of geotechnical data kept in electronic form suitable for visualization generally echoes the distribution of data kept in paper form. Among the 369 data items identified in questions 2.01 and 2.02, approximately 28% are kept as paper only, 27% are kept in electronic form only, and 45% are kept in both formats. On average, the DOTs keep about seven different types of geotechnical data in an electronic format (Figure C6).

2.03 Does your organization have a centralized electronic database for any or all of the geotechnical data listed in Question 2.02?

Among the 37 respondents to this question, approximately 57% have some form of centralized database for geotechnical data.

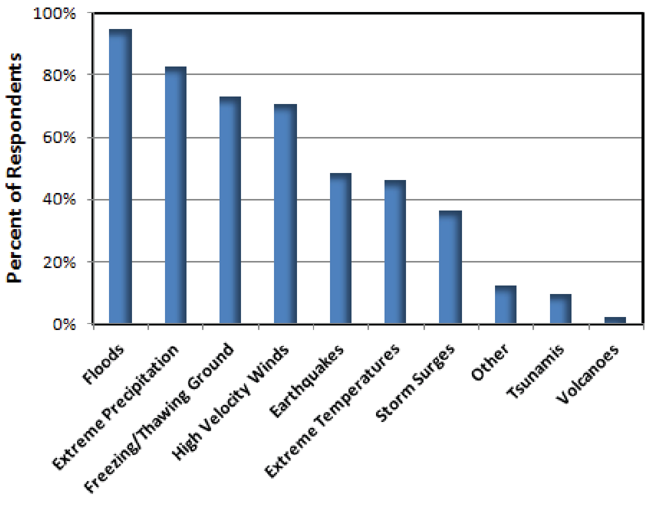

FIGURE C1 Natural phenomena hazards encountered.

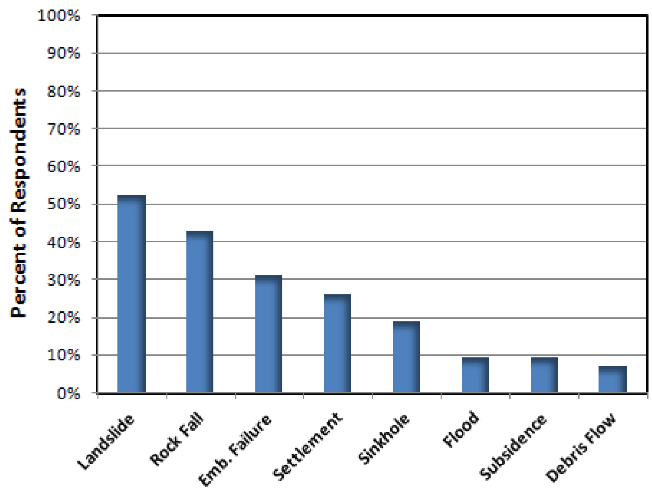

FIGURE C4a Hazards most frequently encountered.

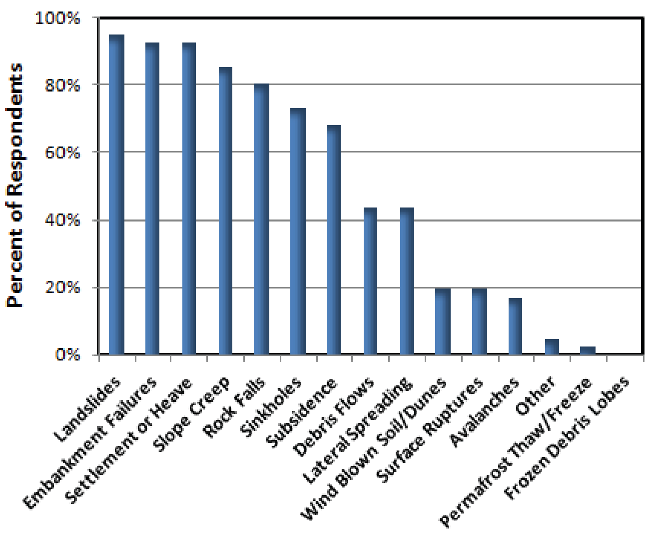

FIGURE C2 Geotechnical hazards encountered.

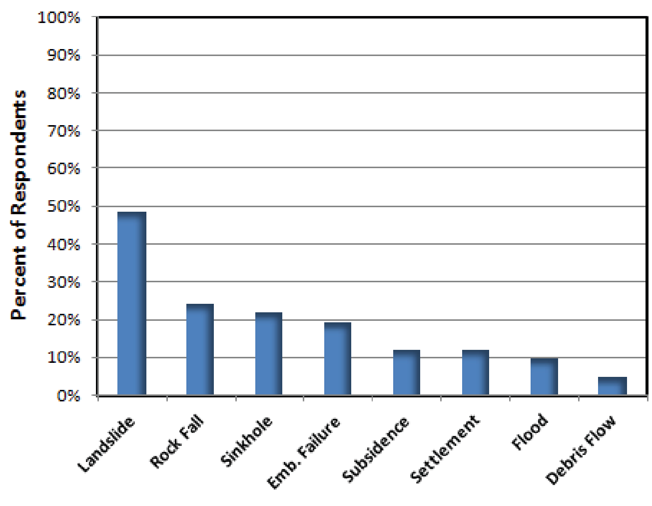

FIGURE C4b Hazards most detrimental to organization.

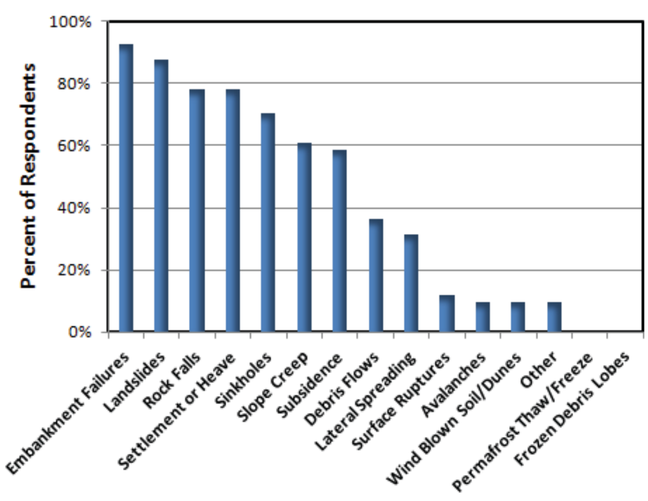

FIGURE C3 Geotechnical hazards responded to.

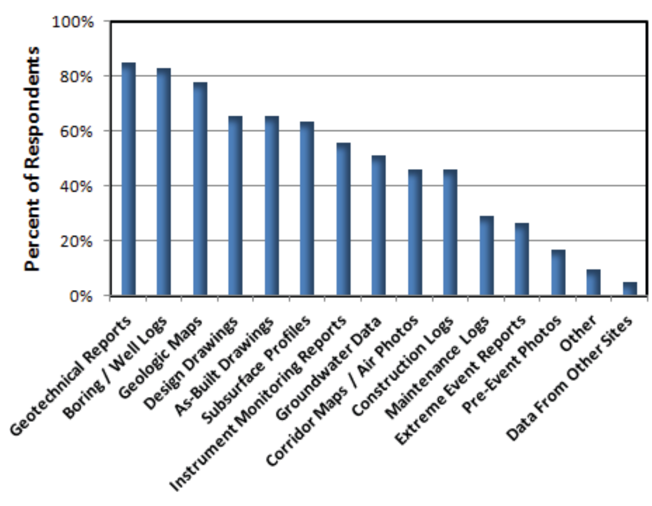

FIGURE C5 Geotechnical data in paper files.

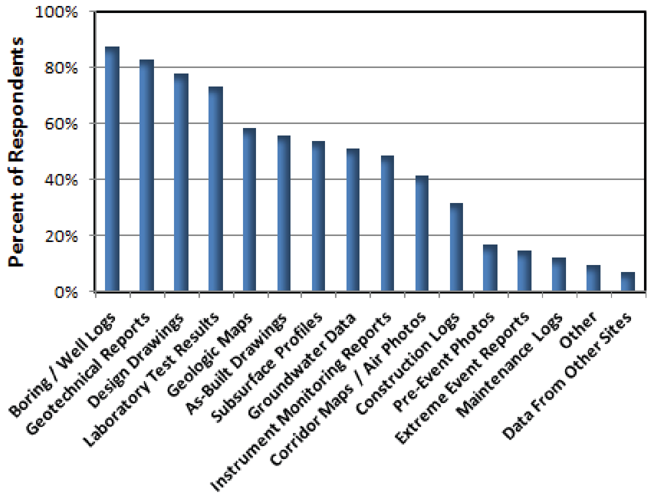

FIGURE C6 Geotechnical data in electronic files.

2.04 If yes to question 2.03, how long is the data retained?

With the exception of one respondent who stated that its geotechnical data would be kept for 50 years, the DOTs that have a centralized database for geotechnical data plan to keep the data on file permanently.

2.05 If yes to question 2.03, what database do you use?

Approximately 59% of DOTs that used a centralized database for geotechnical data have developed their own database. Among the other 41% using a commercial database, most are using some type of boring log and fence diagram software and several DOTs are using the commercial database engines for their geotechnical data.

2.06 Do you use a formal geotechnical data exchange format?

Only one state DOT responded that it is currently using a formal geotechnical data interchange format. The one respondent is following the Data Interchange for Geotechnical and Geo-Environmental Specialists (DIGGS) standard. Information found elsewhere indicates that several states are in the process of adopting a formal geotechnical data interchange format.

2.07 What geotechnical instrumentation does your organization use?

The geotechnical instrument types most commonly used by the DOTs (more than 70% of respondents) include inclinometers, piezometers, settlement gages, and open stand pipe wells. The distribution of instruments is consistent with the most frequently encountered geotechnical hazards of landslides, rockfalls, embankment failures, and settlement issues. On average, each DOT is using five to six different instrument types (Figure C7).

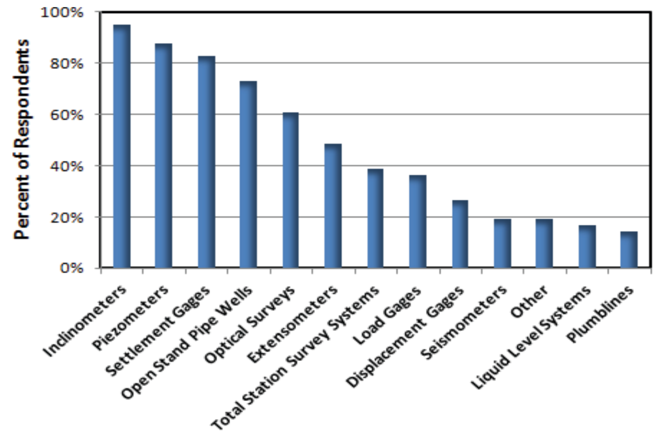

FIGURE C7 Geotechnical instruments used.

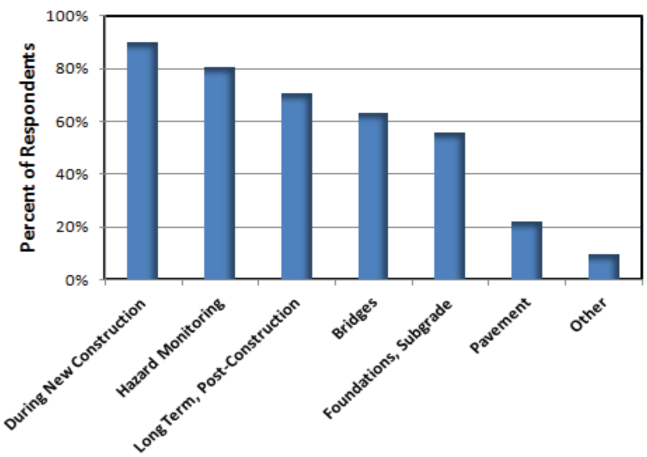

FIGURE C8 Geotechnical instrument project types.

2.08 On what types of projects do you use geotechnical instrumentation?

Among the DOTs that responded to this question, 95% use geotechnical instrumentation to monitor new construction, 81% to monitor hazards and 76% to monitor constructed facilities long-term. About 62% of the DOTs use instrumentation to monitor foundations and subgrade, 62% use instrumentation on their bridges, and 24% use pavement instrumentation (Figure C8).

2.09 How is the decision to use geotechnical instrumentation made?

Ninety-five percent (95%) of the respondents indicate that expert opinion and engineering judgment is used in deciding when and where to use geotechnical instrumentation. However, 62% use that approach as their sole method of selection. The others use that method in combination with some risk analysis method or are required by department policy to use instrumentation (Figure C9).

2.10 How do you collect geotechnical instrumentation data?

Although nearly all of the DOTs (92%) use manual methods to collect their geotechnical instrumentation data, fewer

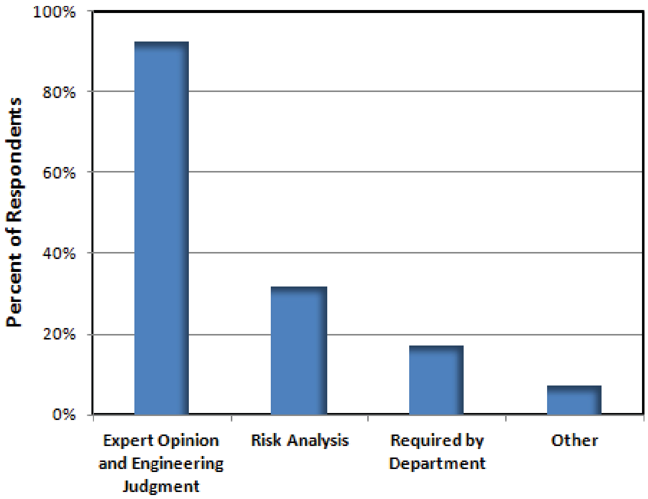

FIGURE C9 Geotechnical instrument decision processes.

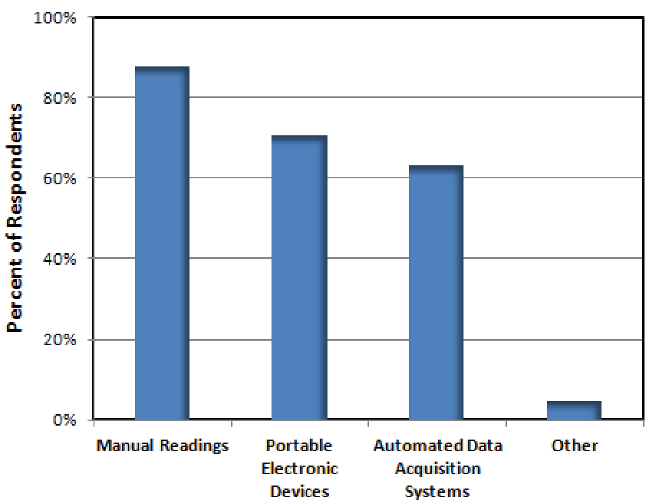

FIGURE C10 Geotechnical instrument data collection.

than 10% use that approach as their sole data collection method. The use of manual reading methods may imply that these data are not accessible for visualization or must be manually keyed in to some system to be available (Figure C10).

2.11 How do you establish hazard mitigation warning and action levels for geotechnical instrumentation data?

As with selection of geotechnical instrumentation, most DOTs (89%) use expert opinion and engineering judgment to set hazard mitigation warning and action levels for geotechnical instrumentation. About 38% use this approach as their sole method of setting warning and action levels. The others use this approach in combination with some level of analysis and testing. One respondent noted that the agency doesn't establish warnings or action levels "due to agency being very averse to potential false alarms" (Figure C11).

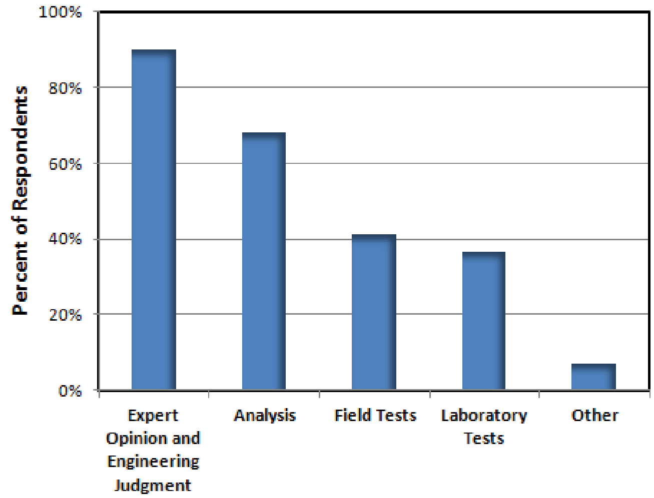

FIGURE C11 Setting mitigation warning and action levels.

2.12 How do you store and process geotechnical instrumentation data?

Approximately 95% of the responding DOTs indicated that they used a spreadsheet application to manage their geotechnical instrumentation data. Thirty-five percent (35%) use this approach as their sole data management method. The others use this approach in combination with vendor, department, and web-based data management systems. The use of spreadsheets to manage geotechnical instrumentation data may be convenient and effective on a short-term, project-specific basis, but will likely not be effective for wider, long-term uses (Figure C12).

2.13 What remote sensing data does your organization use for geotechnical mapping and monitoring?

The most common remote sensing data types reported by the DOTs are views of surface features and topography (e.g.,

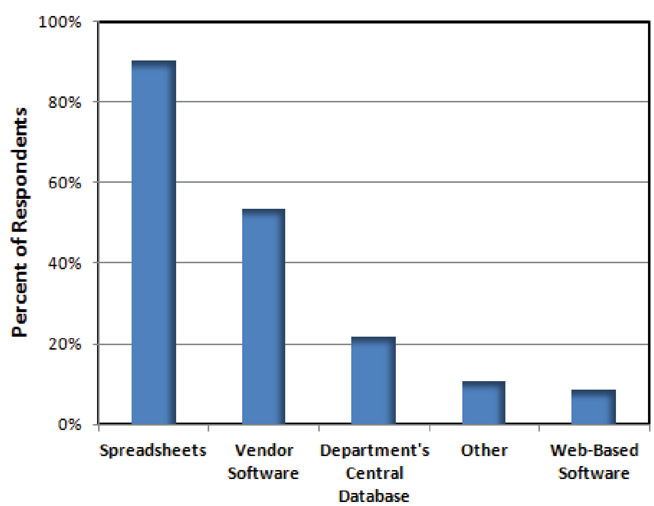

FIGURE C12 Instrument data storage and processing.

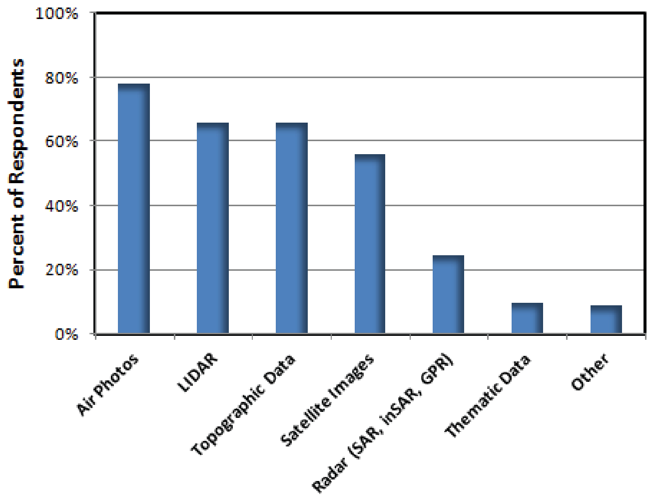

FIGURE C13 Remote sensing data used.

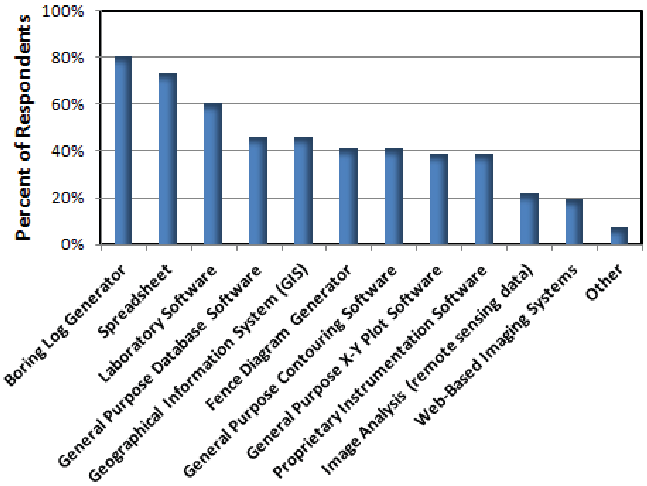

FIGURE C15 Geotechnical data visualization software used.

air photos, LiDAR, topographic maps, and satellite images). Remotely sensed subsurface data such as SAR and inSAR is used by only about 27% of the respondents (Figure C13).

2.14 Where do you obtain remote sensing data for geotechnical mapping and monitoring?

Among the DOTs using remote sensing data for geotechnical mapping and monitoring, the majority are using data from public agencies (e.g., U.S. Geological Survey, U.S. Department of Agriculture) and free or inexpensive commercial sources (Figure C14).

2.15 What geotechnical data visualization (GDV) software does your organization use?

The majority of the DOTs use GDV software for boring logs and laboratory data presentation. The heavy use of spreadsheet software is likely for general purpose x-y plotting. About 40% of the respondents use more complex software such as geographical information systems (GIS) and instrumentation software. Relatively few (about 20%) are using software for image analysis (Figure C15).

The boring log and fence diagram programs in use are also used by some DOTs for laboratory data visualization. Spreadsheet software is used extensively for collecting, processing, and storing geotechnical data. Other commonly noted software packages included limit equilibrium slope stability software and inclinometer data reduction and presentation software.

2.16 Who in your organization uses GDV software?

The predominant users of GDV software in the DOTs are geotechnical engineers (89% of respondents) and geologists (68%). About 20% of the respondents indicate that other

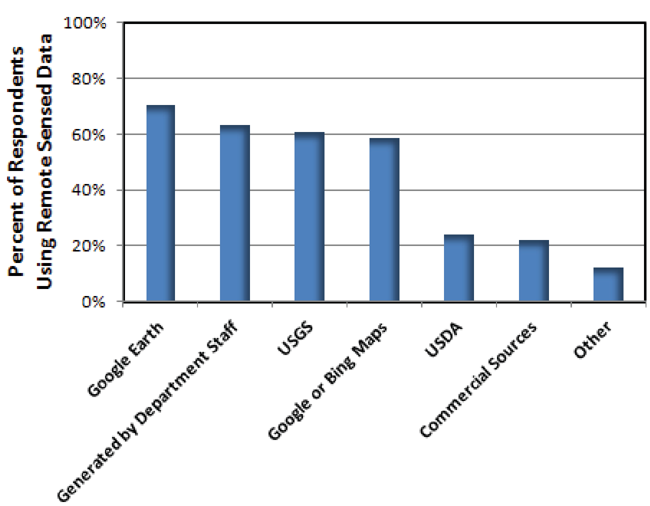

FIGURE C14 Remote sensing data sources.

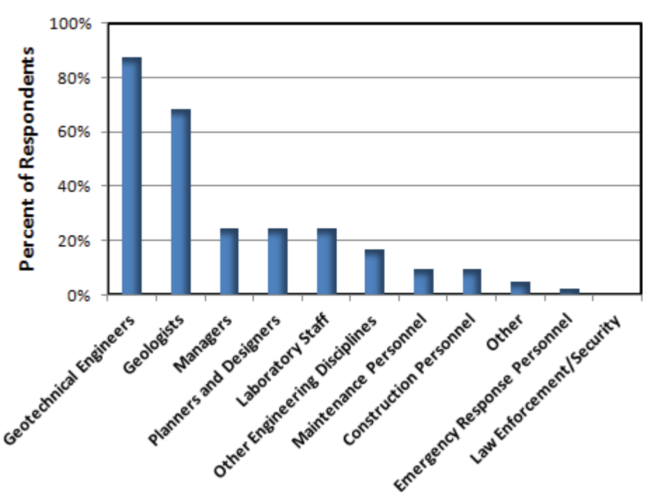

FIGURE C16 Geotechnical data visualization software users.

office staff (e.g., planners, managers) use this software, but fewer than 5% of the respondents indicate that field personnel (e.g., maintenance, construction, emergency responders) use the software. This distribution of users likely indicates that visualization of geotechnical data is not regularly used during disaster response (Figure C16).

SECTION 3. HAZARD MITIGATION TO AVERT DISASTER

3.01 What types of geotechnical hazards have you been able to mitigate impacts through data collection and visualization?

As one might expect, the geotechnical hazards most frequently mitigated successfully echo the distribution of geotechnical hazards encountered (see question 1.02). The geotechnical hazards that are less frequently mitigated successfully in general appear to be those that may be less predictable (e.g., seismic hazards, avalanches) or less commonly encountered (e.g., wind-blown soil, frozen ground). The most common "Other" hazard that was averted through mitigation was bridge and roadway scour (Figure C17).

3.02 What types of geotechnical hazards have you been unable to successfully mitigate?

Nearly half of the respondents (46%) did not identify any unsuccessful hazard mitigation efforts. However, among those who did identify unsuccessful efforts, the most common types were sinkholes and unstable embankments or slopes (Figure C18).

3.03 In what phase of developing hazard mitigation measures do you use GDV?

About two-thirds of the respondents use GDV in one or more phases of developing hazard mitigation measures. The use of these tools is greatest in assessing the hazard and least in planning hazard mitigation, but the sample size is likely too small to distinguish differences in use by development phase. The DOTs use GDV on average in about five of the seven hazard mitigation development phases (Figure C19).

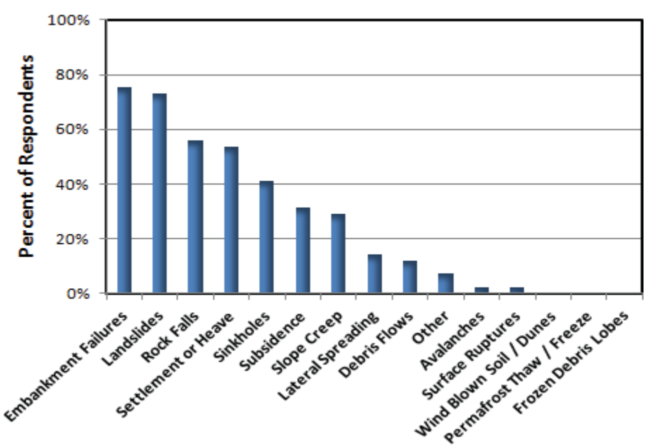

FIGURE C17 Successfully mitigated geotechnical hazards.

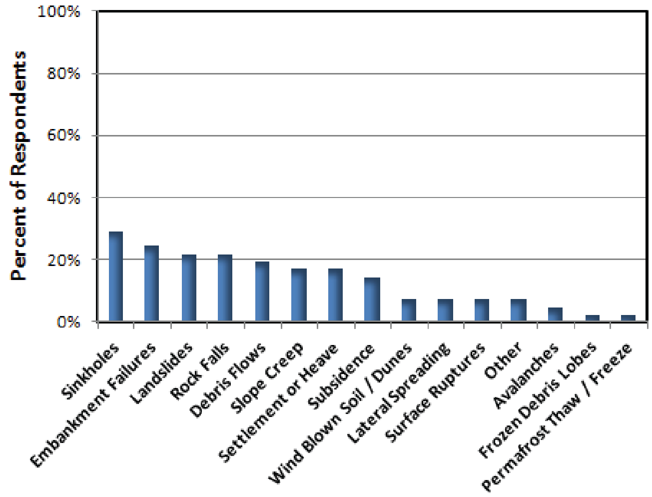

FIGURE C18 Unsuccessfully mitigated geotechnical hazards.

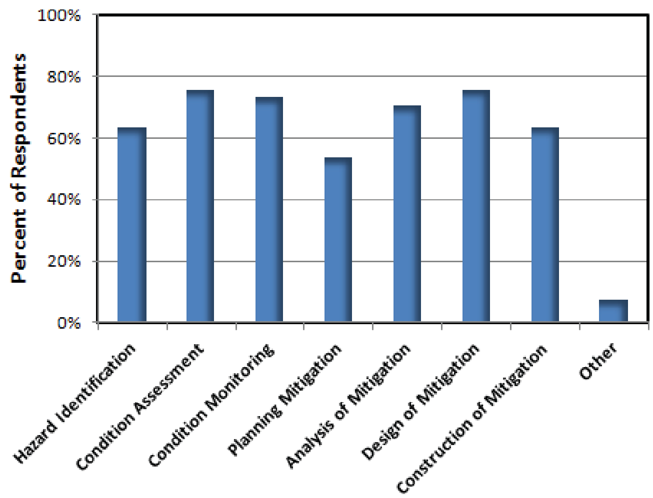

FIGURE C19 Data visualization in hazard mitigation.

3.04 How has GDV contributed to the development of hazard mitigation measures?

About two-thirds of the respondents have identified one or more areas in which GDV contributed to the development of hazard mitigation measures, but the sample size is likely too small to distinguish differences in contributions. On average, the DOTs report that GDV contributes in three to four areas (Figure C20).

3.05 How has GDV contributed to the implementation of hazard mitigation measures?

Approximately 80% of the respondents report that GDV enabled them to implement hazard mitigation measures that

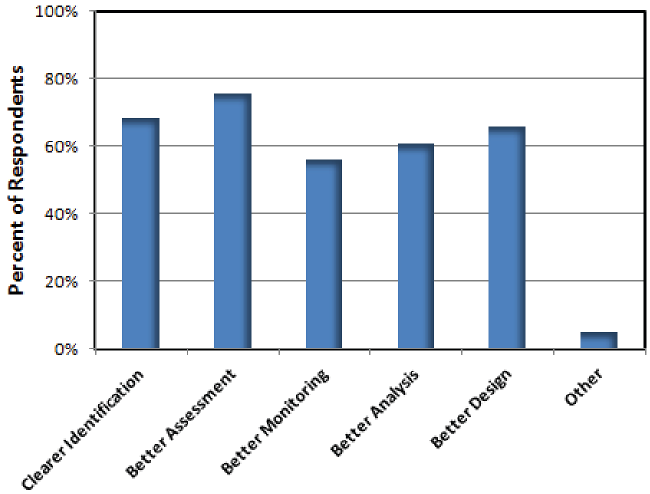

FIGURE C20 Data visualization's contribution to hazard mitigation development.

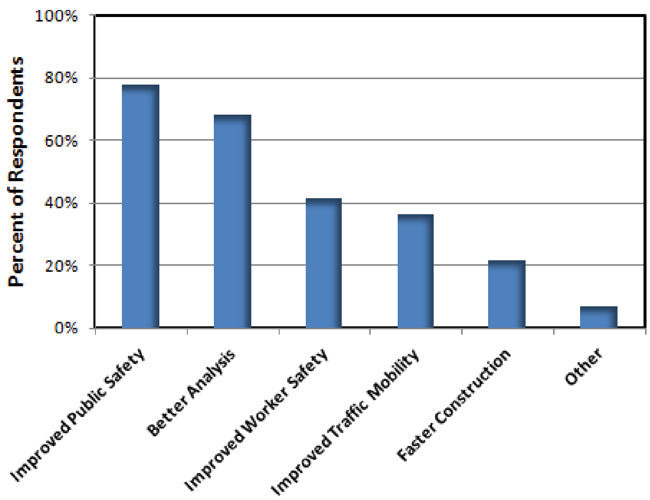

FIGURE C21 Data visualization's contribution to hazard mitigation implementation.

improved public safety. About 40% believed that visualization improved worker safety and traffic mobility during implementation. Only 20% believed that visualization contributed to faster implementation. One respondent reported that visualization resulted in a more economical implementation (Figure C21).

SECTION 4. RESPONDING TO DISASTERS AND EXTREME EVENTS

4.01 What geotechnical data would you find most useful in responding to disasters or extreme events?

The geotechnical data that the respondents would find most useful in responding to disasters include a comprehensive list of topographic maps and subsurface soil, rock, and groundwater data (Figure C22). Although about 70% of the respondents indicated that pre-event photographs would be

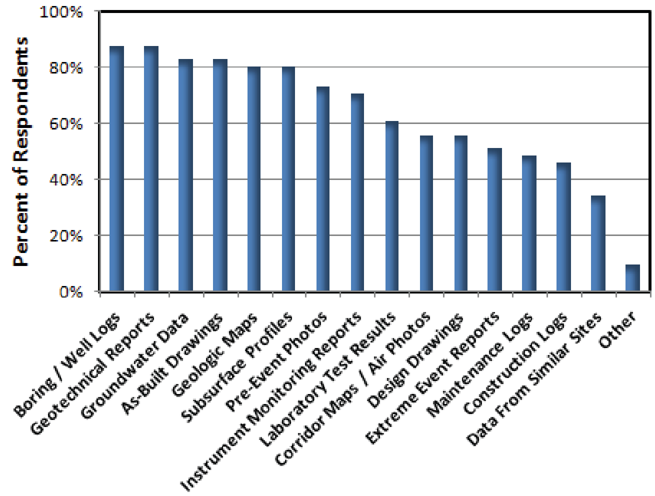

FIGURE C22 Useful geotechnical data for disaster response.

useful, fewer than 20% indicated that these photographs are kept in their electronic files (see question 2.02).

4.02 What geotechnical data do you have on line visual access to in the field when responding to disasters or extreme events?

Approximately 60% of the respondents have on line, visual access in the field to one or more of the geotechnical data elements when responding to disasters. However, only about one-third of them have the data they need. For example, nearly 90% would find visual access to boring log data useful in the field, but only about 30% have that access (Figure C23).

4.03 Does GDV play a role in any of these aspects of your response to disasters or extreme events?

The respondents indicate that the most common role of GDV in disaster response is in the immediate assessment and design of damage repair measures and safety analysis. The

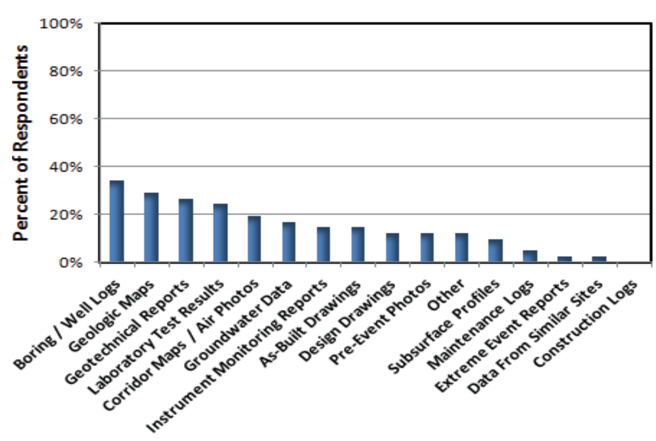

FIGURE C23 Available geotechnical data for disaster response.

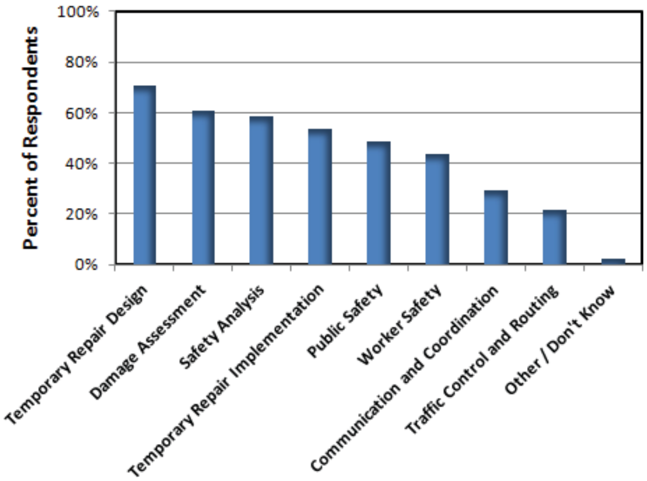

FIGURE C24 Role of geotechnical data in disaster response.

impact of GDV is less on repair implementation and public or worker safety, but, for many DOTs, is clearly important for these purposes (Figure C24).

SECTION 5. LONG-TERM RECOVERY FROM DISASTERS AND EXTREME EVENTS

5.01 What geotechnical data do you find most useful in long-term recovery from disasters or extreme events?

The geotechnical data identified as being most useful for long-term recovery from disasters is generally similar to the data identified as being most useful for disaster response (see Question 4.01). The percentage of respondents identifying a particular data item (e.g., geotechnical reports) is less for this question that for Question 4.01, which is perhaps an indicator of the lesser urgency associated with long-term disaster recovery than with disaster response (Figure C25).

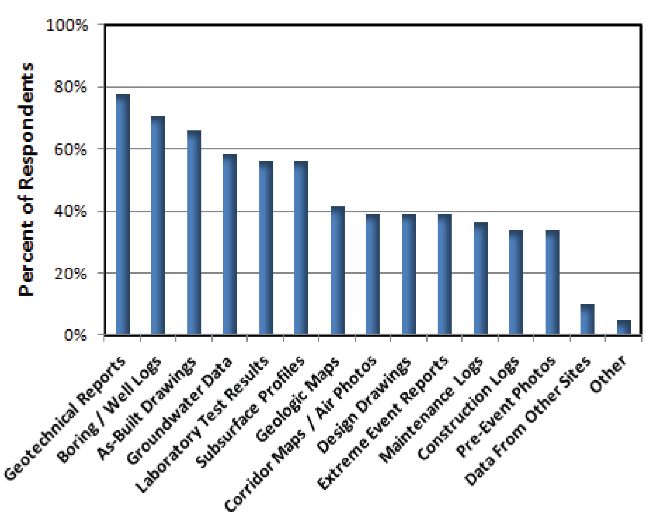

FIGURE C25 Useful geotechnical data for disaster recovery.

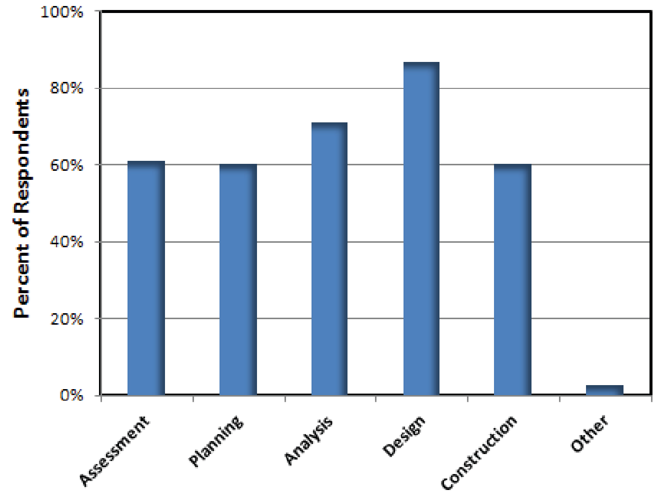

FIGURE C26 Role of geotechnical data in long-term disaster recovery.

5.02 How do you use GDV for long-term recovery from disasters or extreme events?

The DOT geotechnical leaders report that they use GDV most frequently in the design (87%) and analysis (71%) of recovery measures (Figure C26). The responses to this question are generally consistent with responses to a similar question regarding the use of GDV in assessing and implementing geotechnical hazard mitigation measures (see Question 3.03).

5.03 In what way has GDV contributed to long-term recovery from disasters or extreme events?

The top three areas in which visualization of geotechnical data contributes to long-term recovery from geotechnical disasters or extreme events are more economical design and

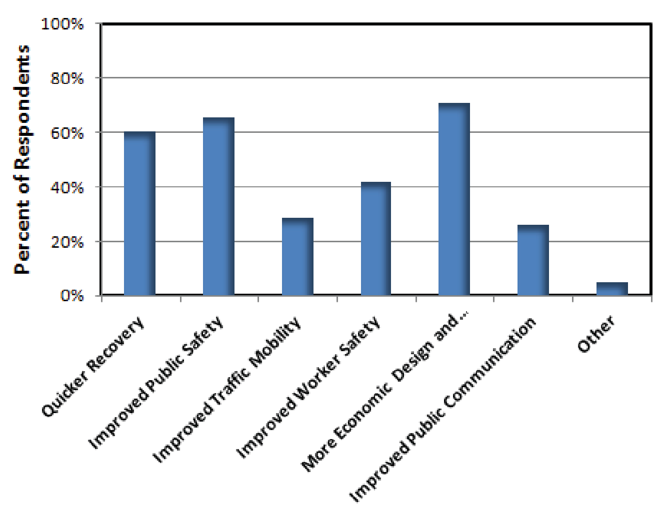

FIGURE C27 Contribution of geotechnical data visualization to long-term disaster recovery.

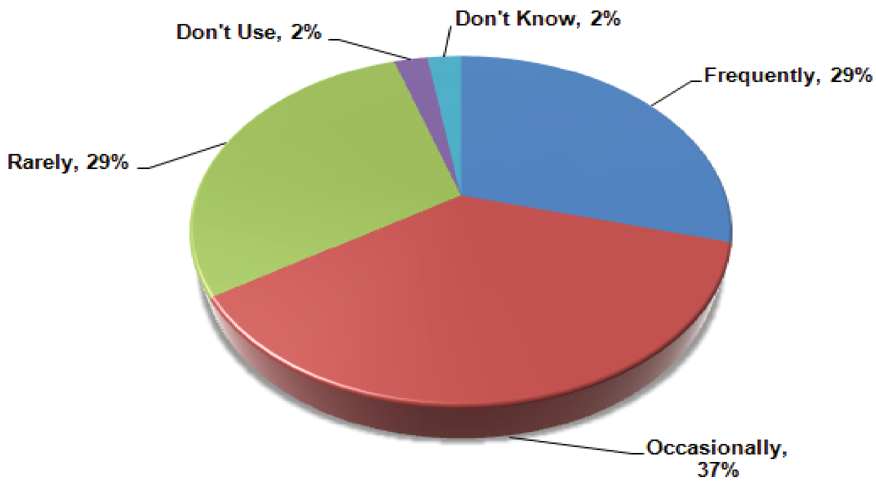

FIGURE C28 Use of geotechnical data visualization tools for disaster or extreme event response.

implementation, improved public safety, and quicker recovery. At least 60% of the DOT geotechnical leaders reported that visualization of geotechnical data made a contribution in these three areas (Figure C27).

SECTION 6. EVALUATION AND OPINION

6.01 *How often does your organization use tools to visualize geotechnical data for disaster or extreme event response and mitigation?*

About 29% of the DOT geotechnical leaders are frequent users of GDV tools for disaster or extreme event response, 37% are occasional users, and 31% rarely or never use these tools (Figure C28). The relatively low level of usage is likely a reflection of the challenge of rapidly retrieving and visualizing appropriate geotechnical data in an environment in which speed is essential but the data and tools are not designed for rapid response.

6.02 *How would you characterize your organization's level of use of GDV tools?*

Approximately half of the DOT geotechnical leaders characterize their organization's use of GDV tools as expert or intermediate level (Figure C29). The current survey did not explore the reasons why some state DOTs are less sophisticated users of visualizations tool than others. However, potential factors may be funding constraints, reliance on consultants to provide this service, or the relatively slower pace at which those agencies are able to adopt emerging technologies.

6.03 *GDV improves our ability to mitigate hazards.* (*agree/disagree*)

About 90% of the DOT geotechnical leaders agree or generally agree that GDV can or does improve their ability to mitigate geotechnical hazards (Figure C30). The 5% who

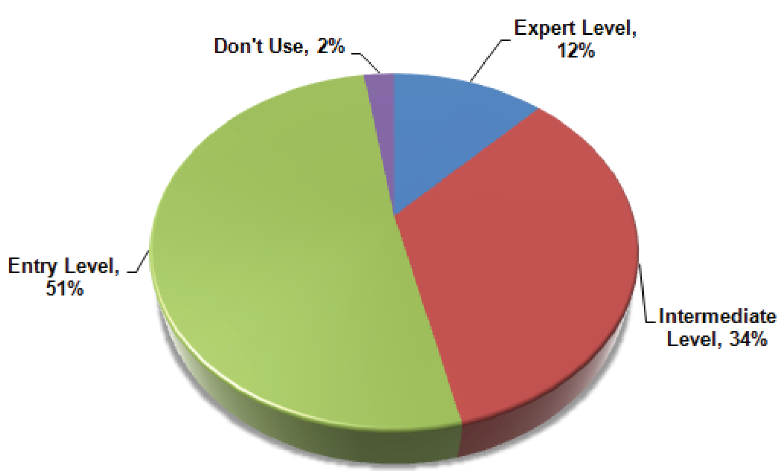

FIGURE C29 Level of use of geotechnical data visualization.

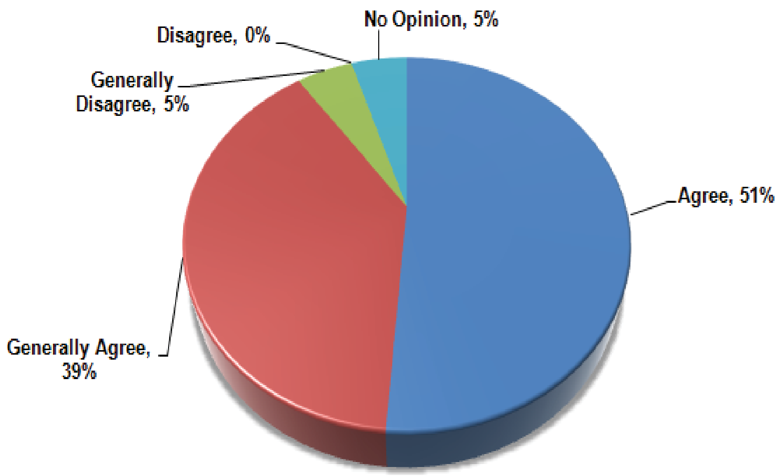

FIGURE C30 Geotechnical data visualization improves hazard mitigation.

generally disagreed with this statement did not offer reasons why they disagreed. However, it is reasonable to speculate that those who generally disagree may consider visualization less critical than other aspects of designing and implementing geotechnical hazard mitigation measures.

6.04 *GDV improves our ability to respond to disasters or extreme events.* (*agree/disagree*)

The response to this statement is similar to the response to the previous question, with approximately 90% of the DOT geotechnical leaders agreeing or generally agreeing with the statement that GDV improves their ability to respond to disasters or extreme events; the difference is that a greater percent more strongly agreed with this statement (Figure C31). Considering that relatively few of the DOTs have visual access to geotechnical data during disaster response (see Question 4.02), it can be assumed that this response indicates that the geotechnical leaders recognize that improved methods of rapidly retrieving and visualizing geotechnical data would improve their response to geotechnical disasters and extreme events.

6.05 *GDV improves our ability to achieve long-term recovery from disasters or extreme events.* (*agree/disagree*)

About 93% of the DOT geotechnical leaders agree or generally agree that GDV can or does improve their ability to achieve long-term recovery from geotechnical disasters or extreme events (Figure C32). This response is consistent with their response to the statement that GDV improves their ability to mitigate hazards (see 6.02). It seems reasonable to assume that this similarity may be the result of the DOTs' ability to more completely access and visualize geotechnical data during hazard mitigation and long-term recovery activities than is possible during disaster response.

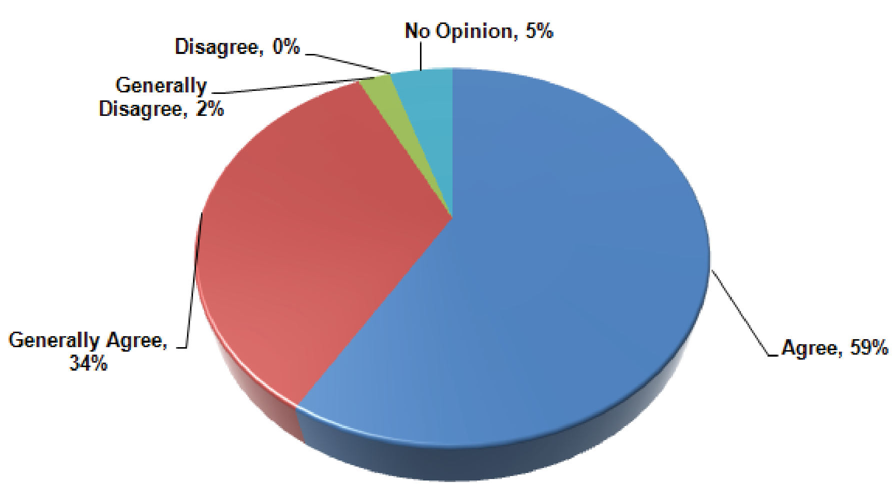

FIGURE C31 Geotechnical data visualization improves disaster response.

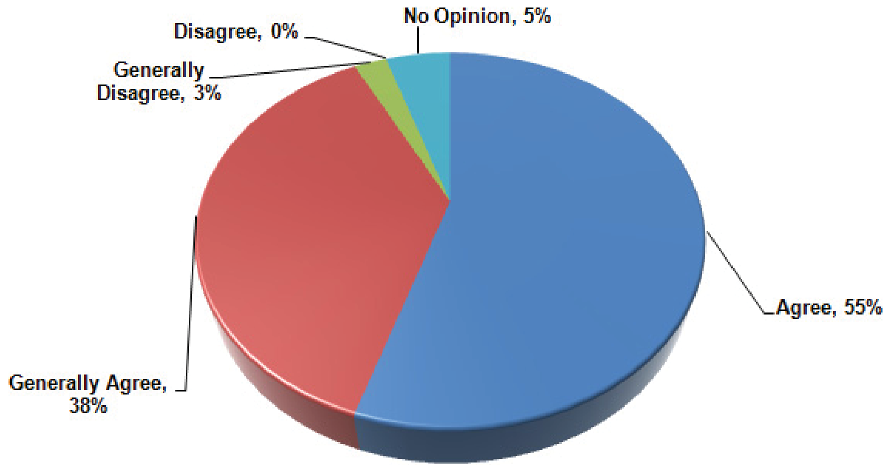

FIGURE C32 Geotechnical data visualization improves disaster recovery.

APPENDIX D

Software Lists

The software titles listed in this appendix are provided for information only. Inclusion on these lists does not imply an endorsement by the National Academy of Sciences or the Transportation Research Board.

More information about these software titles can be found by searching the internet by software title and by accessing the Geotechnical & Geoenvironmental Software Directory at www.ggsd.com/.

Spreadsheet Software

Program	Source
Ability	Commercial
Abykus	Freeware
Accel	Commercial
Accel	Freeware
Apple	Commercial
Bean	Commercial
EasyOffice	Commercial
EditGrid	Commercial
Framework	Commercial
GNU	Commercial
Gnumeric	Commercial
Google	Commercial
GS-Calc	Commercial
Kingsoft	Freeware
LibreOffice	Freeware
Lotus	Commercial
Mariner	Commercial
MarinerPak	Commercial
Microsoft	Commercial
mtcelledit	Commercial
NeoOffice	Commercial
OpenOffice	Commercial
PlanMaker	Commercial
Quattro	Commercial
Sheetster	Freeware
Siag	Freeware
Simple Spreadsheet	Commercial
Smartsheet	Commercial
Spread32	Freeware
StarOffice	Commercial
Tables	Commercial
ThinkFree	Freeware
wikiCalc	Commercial
Xoom	Commercial

Boring Log Generators

Program	Source
AppleCORE	Commercial
BLogPro	Commercial
BOHR	Freeware
Boring Log Database	Commercial
Boring Log Design File Builder	Commercial
BorinGS	Commercial
Coreview	Commercial
DBSOND	Commercial
DCBORE	Commercial
Downhole Explorer	Commercial
Drill&Log	Commercial
DrillKing	Commercial
EasyLog	Commercial
GAP for CADD	Commercial
GEO Software Suite	Commercial
GEODASY Web	Commercial
GEOLOG	Commercial
GeoSmart II	Commercial
GGU-BORELOG	Commercial
GGU-STRATIG	Commercial
gINT Logs	Commercial
LD4 - Boring Log Drafting	Commercial
LithologyColumn	Commercial
Logman 8.0	Commercial
LogPlot	Commercial
LogPlot (PAZ)	Commercial
MacLOGGER	Commercial
Power*Suite	Commercial
Prolog	Commercial
QuickLog	Commercial
SequenceStratColumn	Commercial
Soil Project	Commercial
StratColumn	Commercial
Strater	Commercial
SuLog	Commercial
SuperLog	Commercial
TSPP	Shareware
Well Logger	Shareware
WellCAD	Commercial
WellPlot	Commercial
WinLog Pro	Commercial

Fence Diagram Generators

Program	Source
QuickGIS	Commercial
Spatial Explorer	Commercial
ViewLog	Commercial
ERMA Site Geologist	Commercial
WinFence	Commercial
QuickCross	Commercial
MacSection II	Commercial
Rockworks	Commercial
RockWareGIS	Commercial
Logman 8.0	Commercial
gINT Logs	Commercial

Laboratory Software

Program	Source
Atterberg Limits	Commercial
Atterberg Limits (Quest-Tech)	Commercial
Bulk Density	Commercial
California Bearing Ratio	Commercial
CBR (Quest-Tech)	Commercial
Cc	Commercial
CIRCLE	Freeware
Consolidation	Commercial
Consolidation (Geosystem)	Commercial
ConsolPlot	Commercial
Cris	Shareware
DCCONS	Commercial
DCGLOW	Commercial
DCLIME	Commercial
DCPRESS	Commercial
DCPROC	Commercial
DCSHEAR	Commercial
DCSIEVE	Commercial
Direct Shear	Commercial
DS7 Geotechnical Software	Commercial
EarthFX Data Centre	Commercial
Extended Laboratory System	Commercial
GDSLAB	Commercial
GDSLAB REPORTS	Commercial
Geo Analysis templates	Commercial
GEOCAL	Commercial
GeoSmart II Lab Tool	Commercial
GGU-ATTERBERG	Commercial
GGU-COMPACT	Commercial
GGU-DENSITY	Commercial
GGU-DIRECTSHEAR	Commercial
GGU-ENSLIN	Commercial
GGU-LABPERM	Commercial
GGU-LIME	Commercial
GGU-LOI	Commercial
GGU-OEDOM	Commercial
GGU-SIEVE	Commercial
GGU-TIMESET	Commercial
GGU-TRIAXIAL	Commercial
GGU-UNIAXIAL	Commercial
GGU-WATER	Commercial

Program	Source
Gradlab Gds	Commercial
Grain Size Distribution	Commercial
GSD	Freeware
HELPA Soil Laboratory Software	Commercial
Hydrometer Analysis	Commercial
KeyLAB	Commercial
Lab Bundle	Commercial
Lab Test.xlt	Freeware
LABsys	Commercial
MohrView	Commercial
Moisture Density / Compaction	Commercial
Moisture Density Test	Commercial
OEDOMINT	Freeware
One Point	Shareware
Perma	Commercial
Permeability Test	Commercial
PHASE	Freeware
Proctor Density Report System	Commercial
QESTLab	Commercial
Resistance R-Value	Commercial
R-Value	Commercial
Shear Test	Commercial
Sieve Analysis	Commercial
Sieve Analysis Report System	Commercial
SieveGraph	Commercial
Soil Classification	Commercial
Soilab99	Freeware
SoilClass	Commercial
SoilSeriesPro v.2	Commercial
SP5	Commercial
Swell Consolidation	Commercial
Texture AutoLookup	Freeware
TextureMacro	Freeware
TRIAX	Commercial
Triaxial Shear	Commercial
TRIAXPLT	Freeware
Unconfined Compression	Commercial
UNIPHASE	Freeware
WinCLISP	Commercial
WinSieve	Commercial

Geotechnical Database Software

Program	Source
3Gds	Commercial
BLDM	Commercial
Core-GS	Commercial
GDM	Commercial
GeoBASE	Commercial
GEODASY	Commercial
GEO-LOG 3	Commercial
gINT Professional	Commercial
GIS-Key Winlogs	Commercial
HoleBASE III	Commercial
Hydro GeoLogger	Commercial
PLog Enterprise	Commercial
TECHBASE	Commercial

Contouring Software

Program	Source
3DField	Shareware
Altipoint	Commercial
Axum	Commercial
CONTOUR	Public domain
CoPlot	Commercial
Digital 'X' Model Lite	Commercial
GGU-GEO GRAPH	Commercial
GGU-TIME GRAPH	Commercial
Graphis	Shareware
GWN-SURF	Commercial
ISOMAP	Commercial
MapCalc	Commercial
MathPad	Freeware
McCon	Commercial
QuickSurf	Commercial
QuickSurf Pro	Commercial
Surface III+	Commercial
Surfer	Commercial
Surfit	Freeware
SurGe	Shareware
Survey Tools	Commercial
Trispace	Commercial
Z-CON	Commercial

GIS Software

Program	Source
ArcGIS	Commercial
Capaware	Commercial
Desktop GIS	Commercial
FalconView	Commercial
GRASS	Commercial
gvSIG	Commercial
IDRISI Taiga 16.05	Commercial
ILWIS	Commercial
JUMP	Commercial
Kalypso	Commercial
Mapper	Commercial
MapWindow	Commercial
QGIS	Commercial
SAGA	Commercial
SAGA-GIS	Commercial
TerraView	Commercial
uDig	Commercial
Whitebox	Commercial

Instrumentation Software

Program	Source
3D Tracker	Commercial
Argus	Commercial
DamSmart	Commercial
DigiPro for Windows	Commercial
Flowworks	Commercial
Geo-DMS	Commercial
GEOSCOPE	Commercial
Geotech Monitory System	Commercial
GeoViewer	Commercial
GTilt Plus	Commercial
Inclinalysis	Commercial
INCLI-pro	Commercial
I-Site	Commercial
MonitoringPoint	Commercial
Quickslope	Commercial
Vista Data Vision	Commercial
WINSID	Commercial

Image Analysis Software

Program	Source
ENVI	Commercial
ER Mapper	Commercial
FullPixelSearch	Commercial
JMicroVision	Freeware
Measure	Commercial
ORION	Commercial
Photo Tool	Commercial
SigmaScan Pro	Commercial
WipFrag	Commercial
WipJoint	Commercial

Abbreviations used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation