USGS Approach to Real-Time Estimation of Earthquake-Triggered Ground Failure—Results of 2015 Workshop

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Abstract

The U.S. Geological Survey (USGS) Earthquake Hazards and Landslide Hazards Programs are developing plans to add quantitative hazard assessments of earthquake-triggered landsliding and liquefaction to existing real-time earthquake products (ShakeMap, ShakeCast, PAGER) using open and readily available methodologies and products. To date, prototype global statistical models have been developed and are being refined, improved, and tested. These models are a good foundation, but much work remains to achieve robust and defensible models that meet the needs of end users. In order to establish an implementation plan and identify research priorities, the USGS convened a workshop in Golden, Colorado, in October 2015. This document summarizes current (as of early 2016) capabilities, research and operational priorities, and plans for further studies that were established at this workshop. Specific priorities established during the meeting include (1) developing a suite of alternative models; (2) making use of higher resolution and higher quality data where possible; (3) incorporating newer global and regional datasets and inventories; (4) reducing barriers to accessing inventory datasets; (5) developing methods for using inconsistent or incomplete datasets in aggregate; (6) developing standardized model testing and evaluation methods; (7) improving ShakeMap shaking estimates, particularly as relevant to ground failure, such as including topographic amplification and accounting for spatial variability; and (8) developing vulnerability functions for loss estimates.

Introduction

Minutes after a significant earthquake occurs anywhere in the world, the U.S. Geological Survey (USGS) ShakeMap system (http://earthquake.usgs.gov/shakemap/) rapidly produces estimates of the extent, distribution, and severity of ground shaking by incorporating strong-motion and macroseismic data as they become available (Wald and others, 1999, 2005). ShakeMaps are generated for all widely felt earthquakes as well as those larger than magnitude 5.5 worldwide and magnitude 3.5 in the United States. The USGS Prompt Assessment of Global Earthquakes for Response (PAGER) system (http://earthquake.usgs.gov/data/pager/) assesses potential fatalities and financial losses in aggregate for the event using output from ShakeMap and data on population density and building vulnerability (Earle and others, 2009). The USGS ShakeCast program

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(http://earthquake.usgs.gov/research/software/shakecast/) allows estimates of damage to specific users' facilities such as bridges and buildings (Lin and Wald, 2008; Wald and others, 2008). Both domestic and international users have already adopted these products (for example, the California Department of Transportation and the International Atomic Energy Agency).

ShakeMap, PAGER, and ShakeCast focus primarily on ground shaking; the systems do not yet adequately address hazards and losses resulting from earthquake-triggered landslides and liquefaction. These "secondary" earthquake hazards are commonly overlooked because (1) they are not always a large contributor to losses (Bird and Bommer, 2004; Marano and others, 2010), and (2) both scientific and implementation strategies to include these effects have not been comprehensively addressed. Yet for some earthquakes, ground failure can be a major or even a dominant cause of losses. For example, approximately 20,000 of the 100,000 fatalities caused by the 2008 Wenchuan, China, earthquake were attributed to landslides (Huang and Fan, 2013), and liquefaction losses were extensive from the 2010–2011 Christchurch, New Zealand, earthquake sequence. After the Christchurch event, 65,000 properties required land damage inspections for insurance claims (van Ballegooy and others, 2014) and liquefaction caused major disruptions to infrastructure such as gas, electric, and water systems (Giovinazzi and others, 2011). Direct observations of ground failure may not be available for days or weeks after an earthquake, particularly in remote and mountainous areas that are also the most prone to landsliding.

One of the goals of the USGS geologic hazards programs is to add quantitative assessments of landslide and liquefaction hazards to the aforementioned real-time products. Although some proprietary private sector rapid loss models likely assess the effects of secondary hazards, the USGS aims to provide publicly available hazard methodologies and products. Quantitative ground-failure hazard assessments require a rapid estimate of whether a given earthquake is likely to produce significant landsliding or liquefaction, both in terms of hazard and potential losses. An overall alert level summarizing the expected extent of ground failure, similar to the green to red alert levels currently used by PAGER, would be based on a spatial representation of the probability of landsliding or liquefaction. Longer-term goals include the ability to (1) compute the extent of ground failure, as well as its likelihood; and (2) estimate aggregate human and economic losses resulting from landsliding and liquefaction.

The USGS and collaborators at Indiana University Bloomington and Tufts University have been working on these objectives since a workshop held in 2010. This collaboration has resulted in the collection of numerous landslide and liquefaction inventory datasets (complete or nearly complete maps of ground failure occurrences during past earthquakes) and prototype global statistical models (Nowicki and others, 2014; Zhu and others, 2015b). These models are not yet public because they are currently running in test mode, as described in the following section, and much work remains. The USGS convened a second workshop on October 16 and 19, 2015, in Golden, Colorado. The workshop agenda and list of attendees are provided in appendixes 1 and 2, respectively. The goals of the workshop included a review of the current understanding of earthquake-triggered ground failure; an assessment of high-priority research goals; and a discussion of individual contributions, areas of collaboration, and timing of research products. The remainder of this document summarizes the workshop and discusses the goals that were established at the workshop.

Existing Capabilities and Datasets

Currently (as of early 2016), the only estimate of the effects of secondary hazards in PAGER is a qualitative summary statement indicating whether landsliding or liquefaction has occurred in the past in the epicentral region. Similarly, although ShakeCast has the capacity to estimate ground failure for facility assessments (Wald and others, 2013), that capability is not currently employed because of the gap in data and algorithms required to assemble the necessary susceptibility datasets.

Initial, parallel global statistical models for earthquake-induced landslides (Nowicki and others, 2014) and liquefaction (Zhu and others, 2015b) have been published, but the models continue to be refined and expanded. The models are similar in structure as both are based on logistic regression of past ground failure inventory datasets using sets of predictor variables that are available globally. The initial models were based on the relatively few available complete inventories of earthquake-induced ground failures and calculated at a relatively coarse resolution of 30 arc-seconds (approximately 1 kilometer). The published models neither account for precipitation or other climatic variables nor quantify uncertainties in probability estimates. These models are currently being run automatically at the USGS National Earthquake Information Center for testing. Future versions of these models could be improved by incorporating more inventories, potentially by modifying the methodology to allow the inclusion of incomplete and point datasets.

Several other approaches to estimate landslide potential have been described in the literature and two alternative models that could potentially be applied globally were specifically discussed at the workshop. The two models are (1) an approach described by Godt and others (2008), which is a mechanistic model based on the Newmark method (Newmark, 1965; Jibson, 1993), and (2) a statistical model described by Kritikos and others (2015), which is based on fuzzy logic. The Godt and others (2008) model requires some modifications that are discussed in the "Improving Landslide and Liquefaction Models" section. The Kritikos and others (2015) model would require redevelopment using additional landslide inventories, because the published version was based on just two inventories, and a large amount of work would be needed to obtain global datasets of the required predictor variables.

Currently, no alternative liquefaction models that can be applied globally are available. Several site-specific or regional models exist, but global application would require substantial additional work in terms of data collection, map digitization, modification of existing models, and development of analogous models applicable to new regions (for example, Knudsen and others, 2009; Holzer and others, 2011; Matsuoka and others, 2015). The Federal Emergency Management Agency's Hazus hazard loss model (https://www.fema.gov/hazus/) has modules available to estimate effects from ground displacement (Federal Emergency Management Agency, 2013). However, the modules require detailed input data in the form of susceptibility maps, and the hazard and loss estimates are generalized and based primarily on engineering judgment.

In developing their statistical models, Zhu and others (2015b) and Nowicki (now Jessee) and others (2014) have collected or digitized a much expanded dataset that currently consists of 33 landslide inventories and 27 liquefaction inventories that were previously published by others. Visiting Ph.D. student Hakan Tanyas from the University of Twente in Enschede, Netherlands, has independently accumulated 30 digital earthquake-induced landslide inventories published by others.

Strategies and Challenges

The consensus of the 2015 workshop is that work on improving, finalizing, and implementing the existing statistical models should continue, but other alternative models could be developed and tested as well. This effort will likely result in a suite of models that may include, for example, higher-resolution physics-based methods when the required detailed input datasets are available, as well as more generalized models such as updated versions of the existing global statistical models. To provide a more robust estimate of the spatial distribution, severity, and uncertainty of estimated hazards, either an algorithm for choosing the optimal model for each earthquake could be developed or weighted results from all available models could be combined. Ideally, uncertainties of geospatial and hazard predictor variables could be incorporated and propagated through to probabilistic secondary hazard models. Some authors have proposed approaches to address uncertainties, such as using logic trees (Wang and Rathje, 2015), but this topic requires further development.

Improving Landslide and Liquefaction Models

A preliminary step would be to improve the landslide model of Godt and others (2008), which is based on the Newmark method, by using updated datasets of higher resolution and incorporating precipitation. A major barrier to the usefulness of this and similar physics-based methods is the variability in hillslope material strength, both within a single geologic unit and between different geologic units. This has been shown to be a large source of uncertainty in regional models (Dreyfus and others, 2013) and is a significant research challenge. To address this uncertainty, methods that use geomorphic characteristics along with other proxies calibrated to known strength measurements could be explored, or potentially integrated into a probability function relating Newmark displacements to probability of failure for different types of material (for example, Jibson and others, 2000). To improve the available liquefaction models, the priority is to focus on those models that are based on a surficial geologic unit type (for example, Holzer and others, 2011) and susceptibility proxies such as low elevation, proximity to water bodies, and geologically youthful deposits (Knudsen and others, 2009). Improving the models will require geological and proxy base maps of sufficiently high resolution in terms of both spatial resolution and differentiation of geologic age and depositional environment.

Model Outputs

Existing statistical models yield gridded maps with the value of each cell corresponding to the probability of ground failure. Future models will likely take the same form. However, there is not currently a clear or consistent definition of what exactly the model probabilities represent and it has not been determined what they should represent. The probabilities could represent an index of relative hazard severity, the probability that at least one (potentially very small) landslide or surface manifestation of liquefaction will occur in a given cell, or the spatial extent of a given grid cell that is likely to be affected by ground failure. A model assessment framework needs to be developed that can be applied to ensure compatibility of the outputs from different models, particularly if the models use relative indices; otherwise, the models cannot be directly compared, evaluated, or used in aggregate. Direct comparison of predicted landslide or liquefaction probabilities to observed distributions (inventories) would allow further refinement of probability estimates.

Inventory Datasets

Another challenge in assessing landslide and liquefaction hazards beyond site-specific scales is the major effort required to compile existing inventories that have been gathered and published by many different researchers. These inventories are necessary for model development and validation. The currently openly available inventories, as well as those collected in the future, could be hosted in a standardized way on a USGS Web page. The inventories would be accompanied by metadata and publications summarizing the available inventories. A major objective of this effort, beyond removing a barrier to progress, is to guide future inventory development to the standards required for model development. Additionally, the development of a mechanism for future authors to share their inventories through this Web site could be explored. Many journals and funding agencies now require that digital datasets are made available in perpetuity, so this could be a standardized and centralized way to meet that requirement. Permission and ownership could be a barrier initially and may prevent a complete compilation of all existing datasets, but this barrier may lessen as attitudes continue to shift toward open data and reproducibility.

Existing inventories were compiled by different groups with different methods and priorities, which makes it challenging to use them together to develop models. Statistical sampling methods need to be developed that account for the use of incomplete and inconsistent datasets. For example, sample selection for model development could be weighted by distribution and quality, and strategies for incorporating point datasets with polygon datasets could be developed. Potential approaches on both landslide and liquefaction datasets have already been developed and are being tested (Zhu and others, 2015a; Thompson and others, 2016).

Resolution of Topographic Database

A Shuttle Radar Topography Mission digital elevation model (DEM) of approximately 30-meter (1 arc-second) resolution has recently become available for most of the world (http://earthexplorer.usgs.gov/; Farr and others, 2007). Slope, the key predictor of landslide hazard, was insufficiently captured by the previously available Shuttle Radar Topography Mission DEM of approximately 90-meters (3 arc-seconds) resolution (Farr and others, 2007). To improve slope estimates, the updated 30-meter resolution topographic data could be used in landslide models, including updating the statistical model to higher resolution. The updated data are not as necessary for liquefaction models because slopes are small in susceptible areas. For the conterminous United States, DEMs at the highest resolution could be used, which is a minimum resolution of approximately 10-meter (1/3 arc-second) available through The National Map (http://nationalmap.gov). Using higher-resolution DEMs will require a few adaptations including efficient handling of extremely large data files, such as slope summary statistics (Verdin and others, 2007), as well as estimating landside travel in addition to landslide source areas. Empirical methods for predicting landslide runout, specifically for earthquake-triggered slides, are needed. In general, the travel distances of rainfall-induced slides are greater because of wet soil conditions at the time of movement. Runout estimates could potentially be derived empirically from existing earthquake-induced landslide inventories and topographic data.

Shaking Constraints

In assessing the contribution of ground motion to ground failure hazards, local amplification related both to topography and material contrasts can be an important control on the distribution of triggered landslides (for example, Harp and Jibson, 2002; Meunier and others, 2008; Gischig and others, 2012). However, local amplification is not currently addressed by ShakeMap except where it is measured instrumentally. ShakeMap methodologies likely will be modified to incorporate topographic amplification using new simplified methods that use proxies like slope curvature and relative elevation (for example, Maufroy and others, 2015; Rai and others, 2015). However, the resolution of ShakeMap may not be high enough to resolve important topographic amplifiers except by assigning higher ground-motion variability to such areas. A parallel effort on ShakeMap methodologies (Verros and others, 2016) is producing ShakeMaps that have more realistic geospatial ground-motion variability statistics. These would provide more rigorous ground-motion uncertainty estimates that could be used to reflect this uncertainty in ground failure models. Finally, substantial effort is required to improve the ShakeMap Atlas models of ground motion estimates for recent and historical earthquakes that triggered extensive ground failure (http://earthquake.usgs.gov/earthquakes/shakemap/atlas.php). Such earthquakes will need to be used as calibration (or hindcasting) events for ground failure models.

Estimating Landslide and Liquefaction Effects

USGS collaborators at Indiana University Bloomington have started collecting loss data for seismically induced landslides. Such data could be analyzed to develop a vulnerability function relating the estimated hazard from ground failure to occurrence and population in order to calculate an aggregate range of loss estimates for a given earthquake. An analogous database of the economic effects of liquefaction has not been compiled, but the consensus opinion of workshop participants was that it would be valuable to do so, potentially by using the few well-documented cases such as the 2010–2011 Christchurch, New Zealand; 1995 Kobe, Japan; and 2011 Tohoku, Japan, events.

Initial Ground Failure Hazard Products

Future global products for real-time and scenario events will likely include grid and contour layers (for interactive maps) similar to those currently produced by Did You Feel It? (http://www.usgs.gov/science/cite-view.php?cite=1107) and ShakeMap, as well as static maps of landslide and liquefaction hazard estimates with geographic markers and infrastructure. In addition, higher-resolution maps of critical areas of interest, such as urban areas, could be produced. The secondary hazard probability grids could be made available for internal and external users through the USGS Earthquake Program Web page (http://earthquake.usgs.gov/) as soon as they are produced. ShakeCast clients are one likely category of users of these data. ShakeCast would be a direct beneficiary and recipient of the secondary hazard grids; ShakeCast users would be able to parse the probability grids and use them to evaluate inspection priorities at users' facilities.

Quantitative alert levels based on the aggregated estimate of degree and extent of each hazard could ultimately replace the qualitative descriptions of secondary hazards that are currently reported on PAGER summaries. Landslide and liquefaction summary posters could be developed either separately or in addition to the earthquake summary posters that are released after major events. This would involve developing templates for regional summaries of landslide and liquefaction activity, including past occurrences in the region, that can be automatically produced or edited quickly after an event occurs.

Conclusions

This report outlines a set priorities based on the goals discussed at the second USGS Secondary Hazards Workshop held in October 2015. The required tasks and subtasks are summarized in figure 1. However, these goals and challenges are substantial and require resources that extend beyond the current support base. It was recognized that use of both USGS internal collaborations between the Earthquake Hazards and Landslide Hazards Programs and external contributions through collaborations, USGS grants, postdoctoral researchers, students, and Interagency Personnel Agreements could be beneficial. Some specific challenges might be met through the USGS National Earthquake Hazard Reduction Program external grants program, including (1) developing maps of young geologic units and fill, (2) quantifying shaking and variability in rock strength, and (3) further developing more physically based secondary hazards models. Nonetheless, substantial progress is expected on several of these fronts, and a project plan to identify short-, intermediate-, and long-term priorities based on the identified goals and challenges is being developed.

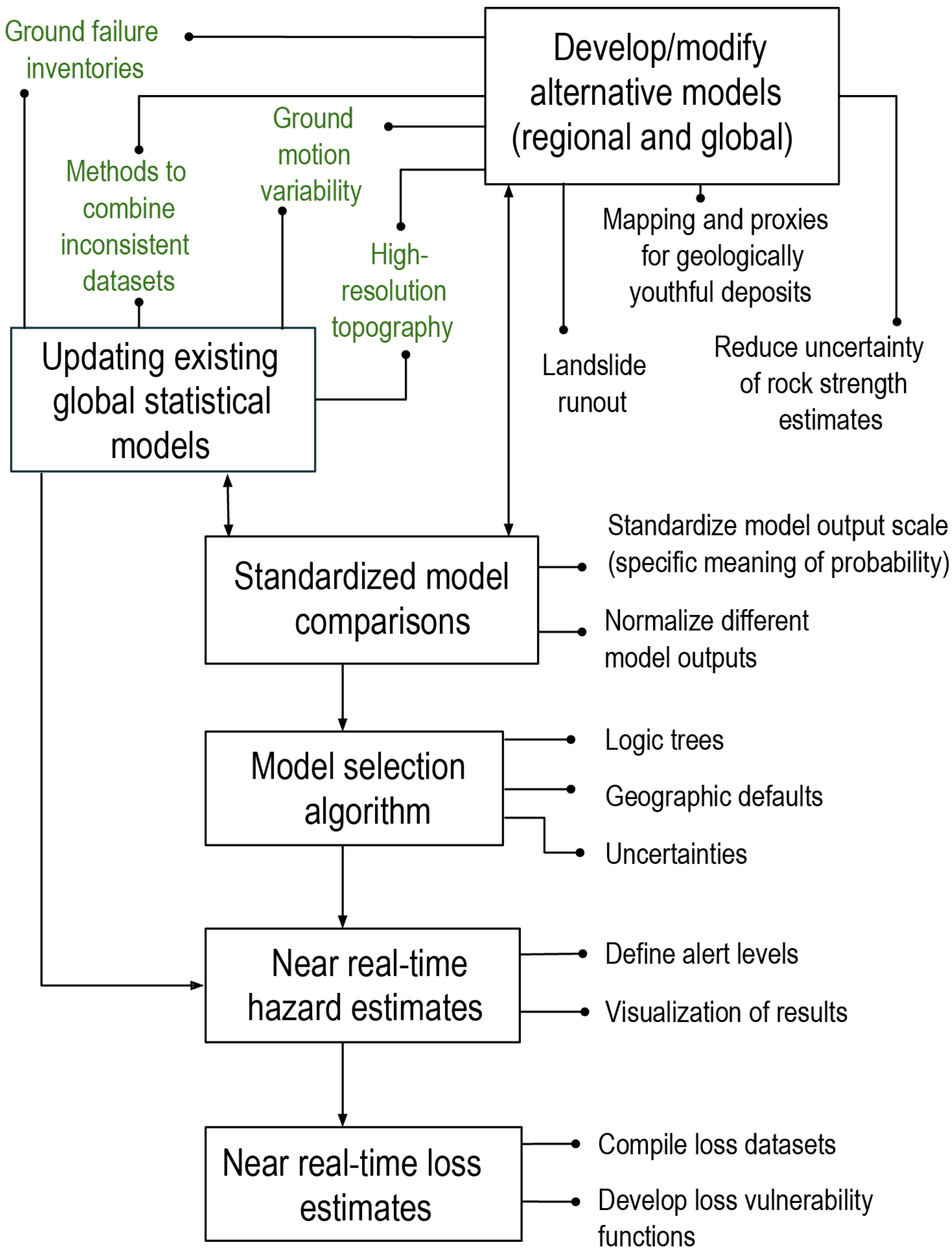

Figure 1. Flow chart summarizing tasks (in boxes) and subtasks described in this document. Green font indicates subtasks that are already in progress.

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Appendix 1. Workshop Agenda

Day 1 (October 16, 2015)—The big picture

Statement of purpose/goals [9–9:30; 30 minutes]

- Self-introductions & logistics [10 minutes]
- Earthquake Program: background, needs & goals; users/products [10 minutes]
- Landslide Program: background, needs & goals [10 minutes]

Overview of where we stand [9:30–11:00; 90 minutes]

- State of the art on seismically induced landslides [less than 20 minutes]
- Overview of available liquefaction & lateral spreading models [less than 20 minutes]
- Update/progress/plans on global statistical landslide model [less than 20 minutes]
- Update/progress/plans on global statistical liquefaction model [less than 20 minutes]
- Implementation of existing models—software, secondary.xml, products, product distribution layer (PDL) [less than 20 minutes]

Products [11:15–12:00; 45 minutes]

- Products we want in approximately 1 year?
- Products we want in a few years?

Improving existing statistical models [1:15–1:45; 30 minutes]

- New predictor datasets, precipitation, arias intensity and duration term, higher resolution

Datasets [1:45–2:15; 30 minutes]

- What do we have, what do we need, problems, solutions
- Assessing quality and comparing inventories
- Newly available global datasets

Moving to more detailed/sophisticated models [2:15–3:00; 45 minutes]

- ShakeCast
- Detailed models for regional implementation
- Compatibility of different models, framework for using multiple models

Basic research needed to move forward [3:15–4:15; 60 minutes]

- Landslides
- Liquefaction

Collaboration Opportunities—[4:15–4:30; 15 minutes]

Day 2 (October 19, 2015)—Details—Facilitated group discussions

Case history issues [8:30–9:30; 1 hour]

- Class balance, null events, point vs. polygon; resolution
- Dealing with dataset inconsistencies, using incomplete datasets

Incorporating uncertainties [9:30–10:00; 30 minutes]

- How to incorporate and propagate uncertainties
- Spatial variability, multiple realizations, statistics

Model validation and comparison [10:00–10:45; 45 minutes]

- Standardized framework for testing, integration & compatibility of different models

Loss data & modeling [11:00–11:45; 45 minutes]

Displaying results [1:15–2:15; 1 hour]

Knowledge Transfer [2:15–3:00; 45 minutes]

Follow up [3:15–4:00; 45 minutes]

Appendix 2. List of Secondary Hazards Workshop Attendees

[USGS, U.S. Geological Survey; ITC, Geo-Information Science and Earth Observation]

Name	Affiliation
Kate Allstadt	USGS Geologic Hazards Science Center, Golden, Colorado
Laurie Baise	Tufts University, Department of Civil and Environmental Engineering, Medford, Massachusetts
Jeffrey Coe	USGS Geologic Hazards Science Center, Golden, Colorado
Jonathan Godt	USGS Landslide Hazards Program, Golden, Colorado
Michael Hamburger	Indiana University Bloomington, Department of Geological Sciences, Bloomington, Indiana
Michael Hearne	USGS Geologic Hazards Science Center, Golden, Colorado
Kishor Jaiswal	USGS Geologic Hazards Science Center, Golden, Colorado
Anna Nowicki Jessee	Indiana University Bloomington, Department of Geological Sciences, Bloomington, Indiana
Randall Jibson	USGS Geologic Hazards Science Center, Golden, Colorado
Keith Knudsen	USGS Earthquake Science Center, Menlo Park, California
Kuo-wan Lin	USGS Geologic Hazards Science Center, Golden, Colorado
Kristin Marano	USGS Geologic Hazards Science Center, Golden, Colorado
William Schulz	USGS Geologic Hazards Science Center, Golden, Colorado
Hakan Tanyas	University of Twente, ITC, Earth Systems Analysis, Enschede, Netherlands
Eric Thompson	USGS Geologic Hazards Science Center, Golden, Colorado
Sarah Verros	USGS Geologic Hazards Science Center, Golden, Colorado
David Wald	USGS Geologic Hazards Science Center, Golden, Colorado
Bruce Worden	USGS Geologic Hazards Science Center, Golden, Colorado
Jing Zhu	Tufts University, Department of Civil and Environmental Engineering, Medford, Massachusetts

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