Slide Detection, Monitoring and Alerting

Requested by
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List of Abbreviations and Acronyms

AASHTO	American Association of State Highway and Transportation Officials
AI	artificial intelligence
AiCP	Artificial intelligence Camera Prototype
ATMS	advanced traffic management system
Caltrans	California Department of Transportation
CCTV	closed-circuit television
CS	cloud system
DAS	distributed acoustic sensing
DOT	department of transportation
EO	Earth observation
ESS	Environmental Sensor Stations
E-W	east-west
EWS	early warning system
GB-InSAR	ground-based radar interferometry
GPM	Global Precipitation Measurement (NASA)
GPRS	ground penetrating radar services
HS	host system
I-94	Interstate 94
IDOT	Illinois Department of Transportation
IMERG	Integrated Multi-satellitE Retrievals for GPM (NASA)
InSAR	interferometric synthetic aperture radar
LaDOTD	Louisiana Department of Transportation and Development
LDM	laser distance measuring devices
LHASA	Landslide Hazard Assessment for Situational Awareness (NASA)
Lo-LEWS	local landslide early warning systems
LSM	landslide susceptibility maps
LSNNS	local sensing node network system
MDOT	Michigan Department of Transportation
MDT	Montana Department of Transportation
ML	machine learning
MVDS	microwave vehicle detection systems
NJDOT	New Jersey Department of Transportation
NLHRR	National Landslide Hazard Risk Reduction
NOAA	National Oceanic and Atmospheric Administration
ODOT	Ohio Department of Transportation
PDC	Pacific Disaster Center (Hawaii)

PSI	persistent scattering interferometry
ROW	right of way
RST	remote-sensing techniques
SAA	shape accelerometer array
SBAS	Small Baseline Subset
SMS	Short Message Service
T4D	Trimble 4D Control (software)
TMC	traffic management center
TRB	Transportation Research Board
UAS	unmanned aircraft systems
UAV	unmanned aerial vehicle
USGS	U.S. Geological Survey
VDV	Vista Data Vision (visualization platform)
VMS	variable message sign
WLAN	wireless local area network
W-NEXCO	West Nippon Expressway Company Ltd.
WSDOT	Washington State Department of Transportation
WSN	wireless sensor network
WYDOT	Wyoming Department of Transportation

Executive Summary

Background

Rural, mountainous routes in California Department of Transportation's (Caltrans') District 2 experience seasonal landslide and rockfall activity, which may cause safety hazards, route closures, or significant traffic delays and detours. These events impact local communities by impeding or eliminating access to essential services and resources.

Caltrans is interested in exploring new technology and detection systems that are used in remote areas where telecommunications is absent. This Preliminary Investigation sought information about early detection, monitoring and alerting best management practices and systems used by other state transportation agencies that experience landslides, rockfalls and other natural hazards, specifically information about surface and subsurface monitoring activities and systems that detect movement and alert traffic management centers (TMCs) when movement occurs. Although some slides in the state are related to wildfire and debris flow, the focus of this investigation is on ongoing, often slow-moving slides.

Information for this investigation was gathered through a survey of state departments of transportation (DOTs) and other stakeholders; outreach to select Caltrans districts about current practices and pilot projects; and a literature search of in-progress and completed domestic and international research.

Summary of Findings

Survey of Practice

An online survey was distributed to state DOT members of the Transportation Research Board (TRB) Geology and Geotechnical Engineering Section and of the American Association of State Highway and Transportation Officials (AASHTO) Committee on Transportation System Operations, and select committee chairs from the TRB Technical Activities Division identified by the project panel. Eight state DOTs and one consultant responded to the survey:

State Transportation Agencies

- Illinois DOT (IDOT)
- Louisiana Department of Transportation and Development (LaDOTD)
- Michigan DOT (MDOT)
- Montana DOT (MDT)
- New Jersey DOT (NJDOT)
- Ohio DOT (ODOT)
- Washington State DOT (WSDOT)
- Wyoming DOT (WYDOT)

Consultant

- Landslide Technology (Cornforth Consultants, Inc.)

Five of these state transportation agencies — IDOT, LaDOTD, MDOT, MDT and ODOT — do not use detection, monitoring and alerting best management practices and technology for landslides, rockfalls and other natural hazards. In Illinois, only minor issues have occurred in one area of the state. LaDOTD would like to initiate a research project to begin geotechnical asset management for slopes and embankments, which are typically man-made and located in urban or suburban areas of the transportation network. MDOT has not installed slide detection equipment, but the respondent provided information about warning systems used with other technologies in the state that monitor snow and icy road conditions.

NJDOT, WSDOT, WYDOT and the consultant reported having experience with detection and early warning systems and practices. The WSDOT and WYDOT respondents briefly described the operating processes of their agencies' systems, from detecting movement to sending an alert:

> WSDOT has established thresholds on its monitoring system. When these thresholds are reached, a text message and email are sent to the monitoring units. The Geotech office checks the alert to ensure it is valid and then notifies Maintenance and, if necessary, conducts a site visit.
>
> In Wyoming, access to real-time data allows the Geology Program to monitor conditions. When an alert is issued, notifications are sent to the WYDOT District Office, WYDOT Maintenance Forces and Highway Patrol if action is needed.

The Landslide Technology consultant has experience providing services to DOTs.

NJDOT currently does not use real-time monitoring systems. Instead, the agency conducts manual evaluations and monitors slopes with the potential for failure. The agency is working to incorporate new technologies, including unmanned aircraft systems (UAS), lidar and terrestrial lidar, to monitor activity in real time and detect changes in slopes.

None of the four agencies used these systems in applications related to debris flow, mudslides or wildfire burn scar areas. WSDOT monitors one rockfall fence using a Geobrugg monitoring product. The agency has also used total stations on rock cuts as they were being constructed. The remainder of its instrumentation is used on landslides. WYDOT monitors slope stability on a temporary basis for construction activities and traffic detours.

Additional information from these four respondents is presented below in six categories:

- Detection and monitoring methods.
- System features.
- Slide behavior assessment.
- Data collection.
- Alerts and notifications.
- System assessment.

<u>Detection and Monitoring Methods</u>

These agencies use multiple methods to detect and monitor land movement, including:

- Lidar.
- Network of weather stations and radio systems.
- Remote sensing techniques (such as satellite radar images).
- Scanning radar systems.
- Surveying and sensing instrumentation.
- Video cameras.

All four agencies responding to the survey use remote sensing techniques. Three respondents (*NJDOT*, *WSDOT* and *Landslide Technology*) use lidar, and three respondents (*WSDOT*, *WYDOT* and *Landslide Technology*) use surveying and sensing instrumentation. Two agencies each use a network of weather stations and radio systems (*WSDOT* and *Landslide Technology*), scanning radar systems (*WSDOT* and *WYDOT*) and video cameras (*WSDOT* and *Landslide Technology*). None of the agencies reported using distributed acoustic sensing (DAS). WSDOT also uses or has used tilt meters, GPS units, total stations, automated piezometers, automated inclinometers (shape arrays), rain gauges, photogrammetry and lasers.

System Features

Survey respondents provided significant detail about agency systems, including products, vendors and manufacturers, and costs associated with the systems, both initial cost incurred and the cost of ongoing operations and maintenance. Product and vendor information is summarized in Table ES1. Additional details about these products along with cost information is presented in the **Detailed Findings** section of this report.

Table ES1. Agency Systems

Agency	Products	Vendors/Manufacturers
New Jersey	ArcGIS lidar layers	Esri
Washington	• InSAR (interferometric synthetic aperture radar) satellite monitoring • Tilt meters, GPS units, total stations, automated piezometers and inclinometers (shape arrays), rain gauges, photogrammetry and lasers	Geoprobe, Navstar, Senceive, Sensemetrics, Sixense
Wyoming	• InSAR satellite monitoring • Ground-based radar, shape array inclinometers, level loggers groundwater monitoring	AssetAssurance Monitoring, IDS Georadar, KorrAI InSAR, Measurand, Solinst
Landslide Technology	Lidar, weather stations and instrumentation, radar, satellite imagery, surveying and sensing products, inclinometers, piezometers, deformation sensors, video cameras	Campbell Scientific, Geokon, Measurerand, RST Instruments, Worldsensing

Slide Behavior Assessment

Survey respondents reported a number of factors that are monitored to assess slide behavior and forecast a potential slide, including:

- Environmental variables.
- Ground vibrations.
- Pore water pressure development.
- Seepage patterns.
- Terrain characteristics.
- Water content.

All four agencies monitor terrain characteristics; three agencies (*NJDOT*, *WSDOT* and *Landslide Technology*) also monitor environmental variables. In addition, NJDOT monitors seepage patterns, and WYDOT monitors water content. None of the agencies monitor ground vibrations.

In addition to these factors, WSDOT observes subsurface movement with inclinometers and surface deformation with change analysis from terrestrial lidar or airborne lidar/point cloud data, WYDOT supplements conventional instrumentation by monitoring temporary excavation and slope movements, and Landslide Technology has monitored displacement rate.

Data Collection

Among the four agencies, data is typically collected through instrumentation and proprietary practices, and transmitted through radio and cellular technology:

> NJDOT collects raw data, but currently has limited post-processing capabilities. The agency is evaluating ways to improve these capabilities so it can use the data.
>
> WSDOT uses instrumentation to collect and transfer data through radio signals to a nearby gateway. The data is then transmitted through cell towers or satellites back to a server that makes it available on the web through an internet browser.
>
> WYDOT uses AssetAssurance Monitoring to provide continual monitoring and alerts. Data is accessed through proprietary software for real-time monitoring. Inclinometer and level loggers are shared through a cloud-based subscription. Data gathered through site collection is transmitted through the internet, satellite communications and other devices.
>
> Landslide Technology collects data through radio and cellular technology, site visits and manual collection methods.

Alerts and Notifications

In addition to sharing details about detection and monitoring methods, the survey respondents described alerting and notification practices implemented by their agencies, including how alerts are received and delivered within their agencies, and how the traveling public is notified of hazardous incidents or road closures.

NJDOT, WSDOT and WYDOT maintenance operations receive alerts from early warning systems. Other departments receiving alerts include staff in NJDOT's geotechnical engineering and geology, operations and emergency management (if there is a mass movement event) divisions; Washington's State Geotechnical Office; and WYDOT's district office, Geology Program and Highway Patrol. At Landslide Technology, consultants receive the alerts. None of the agencies participating in the survey send alerts to TMCs.

WSDOT, WYDOT and Landslide Technology send alerts by email and by SMS (Short Message Service) text messaging service. WSDOT and WYDOT also send alerts by telephone. NJDOT hasn't established a system for sending alerts related to land subsidence. Currently the data is collected during field inspections and evaluated at the office.

To inform the public about a hazardous incident, NJDOT uses the media, news alerts and road signage to alert travelers to a mass movement event. In Washington, the State Geotechnical Office or WSDOT Maintenance conducts a site visit to assess road conditions and closes the highway if conditions warrant. WYDOT provides travel alerts through the WYDOT TMC notification system, which includes a website and variable message signs (VMS). If actions are needed, the agency also informs district maintenance offices and the Highway Patrol. None of the survey respondents reported actuating a flashing beacon, generating an audio-visual alarm or posting a notice to the 511 real-time traveler information service. To notify the public about a road closure caused by a slide, NJDOT, WSDOT and WYDOT use a manual process that requires intervention from an operator.

System Assessment

WSDOT, WYDOT and Landslide Technology noted the value of receiving real-time data. This data allows Landslide Technology and WYDOT to make informed decisions and identify appropriate mitigation and risk reduction activities, which enhances the safety of the traveling public and agency staff. The WSDOT respondent cited the cost-efficiency of systems that are "dialed in," noting the dollars saved throughout the process — from site visits to data collection. These systems also allow agencies to pinpoint movement to weather events and groundwater elevations, and warn agencies that a potential problem is developing.

Three respondents also reported challenges with early warning systems and practices, including adequate power from solar panels and batteries to meet system operation needs (*WSDOT* and *WYDOT*). Some WSDOT systems also need cellular coverage, which is not available in all remote areas where landslides are located. Vandalism and equipment theft are issues in Washington. WYDOT faced initial challenges acquiring communication devices to transmit data. Current obstacles in Wyoming include logistical challenges with high-altitude, mountainous terrain and access to equipment in winter weather. NJDOT, which is preparing to use real-time monitoring systems, faces challenges with system funding, implementation and management, and with staff training.

Consultation with Experts

Select Caltrans districts and university partners were contacted to gather information about the following current pilot studies and construction projects:

- District 1: Partnering with California Polytechnic State University, San Luis Obispo, in a pilot evaluation using DAS technology to monitor seismic activity for highway maintenance.
- District 2: Partnering with the University of California, Davis in a pilot evaluation using DAS technology for vehicle detection and monitoring in transportation management.
- District 5: Potential detection and monitoring efforts related to land movement activity.
- District 10: Rock slide technology used for the Ferguson Rock Shed Project in Mariposa County.

Three districts described current activities related to these projects, which are summarized below:

- **District 2**. This pilot only recently got underway (launched October 17, 2024). Technologies have not yet been deployed in the field, and research data is not yet available.
- **District 5**. A rock slide construction project is underway at Regent's Slide following a hillside collapse. Remote monitoring equipment includes a prism in a total station survey (Trimble T4D Control hardware and software) and daily UAS flights that monitor displacement and changing site conditions (cut and fill volume). In-ground monitoring equipment includes shape arrays and vibrating wire piezometers to detect groundwater and ground movement. The Vista Data Vision (VDV) visualization platform presents raw data as plots of displacement and groundwater elevations. The base station also includes solar arrays and batteries for power and Starlink internet service to transmit data.

  Key factors monitored include displacement (the primary focus), groundwater elevation and change detection. Additional data is collected about the health of the monitoring systems. The datastream is checked daily (manually), and information is integrated with other data to inform decisions about safety and construction project activities.

Because some of the equipment used at Regent's Slide has been repurposed from other projects, it is difficult to estimate the cost of the technologies. A ballpark estimate is $200,000 upfront and $100,000 annually for operations.

A challenge with remote sensing is that systems are not automated. Uninterrupted power and internet service are needed to collect data. Maintaining power during adverse weather and other events can be difficult, which can cause a lapse in data collection and require human intervention to repair.

- **District 10**. The Ferguson Rock Shed Project is restoring access to State Route 140 in Mariposa County by building a protective rock shed structure at the site. Geotechnical instrumentation has been installed at four monitoring stations to monitor the rock slide during construction. Subsurface instruments, including vibrating wire piezometers, shape accelerometer arrays and time domain reflectometry sensors, monitor groundwater levels and subsurface deformation. An automatic data collection and transmission system, including data loggers, weather instruments (rain gauges, thermistors and barometers), sensor interfaces and radio telemetry system, monitors the sensors in near real time. The equipment uses an existing data link (wireless Ethernet bridge) to transmit subsurface monitoring data to the internet.

  The automated monitoring systems are programmed to record data at one-hour intervals. Data is then stored locally on data loggers and transmitted via radio link hourly to the internet. VDV servers store and process the data, allowing users to access it in near real time.

Related Research and Resources

A literature search of publicly available domestic and international in-progress and published research identified resources that are organized into two categories:

- Highways.
- Railways.

These categories are further organized according to national, state and international research and resources. Tables summarizing these publications are presented by topic area beginning on page 11. Each table provides the publication or project title, the year of publication if research is completed, and a brief description of the resource. Significantly more detail about each resource can be found in the **Detailed Findings** section of this report.

Gaps in Findings

Despite a broad distribution, the survey received responses from eight agencies — a relatively limited response. Of those eight agencies, only four have experience with detection, monitoring and alerting systems and technologies used for landslides, rockfalls and other natural hazards. In addition, only two of the four Caltrans districts were able to provide information about detection and monitoring technologies at their construction sites. Most of the published literature that is publicly available is associated with slide activity related to debris flow and wildfires.

Next Steps

Moving forward, Caltrans could consider:

- Contacting the four agencies participating in the survey to learn more about agency practices, especially NJDOT as it gains experience using real-time monitoring systems.
- Reaching out directly to agencies not participating in the survey to potentially obtain useful information about other agencies' experience.
- Engaging with the National Landslide Hazard Risk Reduction Working Group to network with emergency managers, geoscientists, planners and other professionals about potential technologies and systems for use in early slide detection, monitoring and alerting.
- Continuing to monitor projects within the Caltrans districts interviewed in this report for relevant information about detection and monitoring practices and technologies.
- Reviewing the literature for applicable information about detection and monitoring systems.

Table ES2. Highways: National Research and Resources

Publication or Resource (Year)	Excerpt from Abstract or Description of Resource
National Landslide Hazard Risk Reduction (NLHRR) Working Group (undated)	Presents organizational details about the NLHRR working group, which is supported by the U.S. Geological Survey Landslide Hazards Program "to share best practice methods, develop collaborations, enhance communication, enable training opportunities and inspire the co-creation of new initiatives."
National Strategy for Landslide Loss Reduction (2022)	Provides a framework for the creation of an interagency management plan that describes the programs, projects, workforce and budgets required to carry out the national strategy of using landslide data and science to support land management, infrastructure, planning and emergency response decisions.

Table ES3. Highways: State Research and Resources

Publication or Resource (Year)	State	Excerpt from Abstract or Description of Resource
Shannon & Wilson's State-of-the-Art Monitoring System Prevents Flooding on Colorado's US 36 (2023)	Colorado	Summarizes the return on investment of this project. The continual data provided by sensemetrics [sensors] has improved safety and enhanced asset management along US 36. Data from the sensors provides a longer-term picture to understand ground and rock movements, helping prevent damage and ensure safety.
NASA Partners with Pacific Disaster Center on New Landslide Hazard Assessment and Warning System (2023)	Hawaii	Describes a model that was integrated into the DisasterAWARE platform, which provides early warning and risk assessment services for 19 types of natural hazards.
Research in Progress: The Willamette Watershed Project: A Resilient Communications, Monitoring and Alerting Network for the Willamette Valley (undated)	Oregon	Describes a project to "lay new communications infrastructure, including a new backbone network of fiber cables and a network of fixed wireless sensors." Monitoring and alerting sensors will be installed for a variety of applications, including landslide warning and detection systems in key transportation corridors.
Artificial Intelligence (AI) for Building a Landslide Inventory and Advanced Landslide Warning System in PA (2023)	Pennsylvania	Presents the results of a study aiming at developing artificial intelligence (AI) models for advanced warning of rainfall-induced landslides for unstable slopes above or below state-maintained roadways in Pennsylvania.

Table ES4. Highways: International Research and Resources

Publication or Resource (Year)	Continent/ Country	Excerpt from Abstract or Description of Resource
Monitoring Strategies for Local Landslide Early Warning Systems (2019)	Multiple	Describes and analyzes monitoring strategies implemented within local landslide early warning systems that are operational throughout the world.
Monitoring Slow-Moving Deep-Seated Landslide Using PSI Technique: A Case Study of a Potential Sliding Slope from Southern Taiwan (2025)	Asia/Taiwan	Describes the deformation rates at a potential landslide site using the persistent scattering interferometry (PSI) technique.

Publication or Resource (Year)	Continent/ Country	Excerpt from Abstract or Description of Resource
Entering the Era of Earth Observation-Based Landslide Warning Systems: A Novel and Exciting Framework (2020)	Asia/China	Uses satellite radar observations to detect deformation precursors of catastrophic landslides and deliver real-time early warnings.
Development of a Slope Disaster Monitoring System for Expressway Operation and Maintenance Control (2018)	Asia/Japan	Describes the development of an advanced slope disaster monitoring system for practical use on expressways in Japan.
Wireless Sensor Network in Landslide Monitoring System with Remote Data Management (2018)	Asia/Japan	Describes a system that uses a wireless sensor network to monitor landslide disasters in remote areas.
Landslide Monitoring and Maintenance Plan Along Infrastructure: The Example of the Maratea Major Rockfall (Southern Italy) (2025)	Europe/Italy	Describes the data collection and the reconstruction of rockfall kinematics, as well as the susceptibility analysis carried out for the development of the monitoring system that allowed the reopening of the road after a rockfall.
Innovative Extenso-Inclinometer for Slow-Moving Deep-Seated Landslide Monitoring in an Early Warning Perspective (2024)	Europe/Italy	Discusses the use of a smart extenso-inclinometer within an early warning system for slow-moving landslides.
Real-Time Detection and Management of Rockfall Hazards by Ground-Based Doppler Radar (2024)	Europe/Italy	Describes the use of a ground-based Doppler radar that performs real-time, long-range, wide-area detection and tracking of rockfalls and related slope hazards. The Doppler radar was programmed to actuate a pair of traffic lights so that a predefined exclusion zone could instantly be enforced for approaching vehicles upon initial movement detection.
Rockfall Early Warning System for Enhancing Traffic Safety (2024)	Europe/Italy	Presents a case study of the early warning monitoring system made to prevent or reduce risks in case of rock mass deformation and consequent rockfalls.
An Innovative Early Warning System for Rockfall Protection Systems and Events (2023)	Europe/Italy	Describes an innovative alert system developed to verify if a rockfall or debris flow protection system is impacted, or if an event, such as a landslide or rockfall, might happen.
Long-Term Evolution and Early Warning Strategies for Complex Rockslides by Real-Time Monitoring (2017)	Europe/Italy	Examines monitoring data for a rockslide in the Central Italian Alps, collected since 1997 by ground-based and remote-sensing techniques.
Remote Monitoring System PTH 83 Shell River Landslide, Russell, Manitoba (2017)	North America/Canada	Describes a remote monitoring system at the site to detect landslide movements and provide early warnings of dangerous road conditions. The system was designed to send text message and email alerts to notify department maintenance staff of abnormal landslide movements.

Table ES5. Railways: National Research and Resources

Publication or Resource (Year)	Excerpt from Abstract or Description of Resource
Detection of Rockfall-Prone Areas Through InSAR-SBAS Analysis (2024)	Presents two case studies that use Small Baseline Subset (SBAS) analysis to identify areas along the railroad right of way that exhibit increased geohazard risk. The case studies underscore how satellite-based monitoring can enhance early warning systems for geohazards and assist disaster mitigation and preparedness efforts.

Table ES6. Railways: International Research and Resources

Publication or Resource (Year)	Continent/ Country	Excerpt from Abstract or Description of Resource
Monitoring and Early Warning Method for a Rockfall Along Railways Based on Vibration Signal Characteristics (2019)	Asia/China	Establishes a set of monitoring and early warning systems for rockfall disasters along the railway based on the analysis of vibration signal characteristics.
Rockfall Alarm System for Railway Monitoring: Integrating Seismic Detection, Localization and Characterization (2024)	Europe	Develops a seismic processing workflow for rockfall early warning, powered by dense arrays deployed along the track, indicating its potential in near real-time rockfall alarm systems.
Towards Seismic-Powered Rockfall Alarm Systems for Railway Monitoring (2023)	Europe	Presents rockfall alarm systems for railway monitoring powered by real-time automated seismic processing.
Detecting Landslides and Rockfalls — Preventing Railway Accidents (2023)	Europe	Describes a Sensonic landslide and rockfall alerting system, which is based on fiber-optic DAS.
Rock Falls Impacting Railway Tracks: Detection Analysis Through an Artificial Intelligence Camera Prototype (2017)	Europe/Italy	Describes an AI camera prototype for real-time monitoring that was integrated in a multisensor monitoring system devoted to rockfall detection.
Rockfall Detection Using LiDAR and Deep Learning (2022)	North America/Canada	Investigates the potential of integrating sophisticated deep learning architectures into dynamic rockfall database population processes to eliminate manual classification of rockfall events in change detection data when building AI-based early warning systems.

Detailed Findings

Background

Detection and monitoring systems are used to identify and observe land movement in areas near roadways that are prone to landslides, rockfalls and other geological hazards. These systems use various technologies and practices to detect and respond to natural hazards, including sensors (pore pressure sensors, vibration sensors and rain gauges); remote sensing (lidar, satellite and ground-based interferometry); image processing and analysis; and visual inspections. Sensors collect data continuously, which is analyzed in real time to detect changes and potential hazards. When a slide is detected, the system automatically alerts appropriate agency staff who responds to the event.

Rural, mountainous routes in California Department of Transportation's (Caltrans') District 2 experience seasonal landslide and rockfall activity. This movement may cause safety hazards, route closures or significant traffic delays, resulting in detours that are impractical at best and often nonexistent. These events impact local residents by impeding or eliminating their access to essential services and the resources that they need.

To address this issue, Caltrans is interested in exploring new technology and detection systems that are used in remote areas where telecommunications is absent. This Preliminary Investigation sought information about early detection, monitoring and alerting best management practices and systems used by other state transportation agencies that experience landslides, rockfalls and other natural hazards. Caltrans was specifically interested in information about surface and subsurface monitoring activities and systems that are used to detect movement in a slide area and that alert traffic management centers (TMCs) when movement occurs. Although slides related to wildfire and debris flow occur in the state, the focus of this investigation is on ongoing, often slow-moving slides.

Information for this investigation was gathered through a survey of state departments of transportation (DOTs) and other stakeholders; outreach to select Caltrans districts about current practices and pilot projects; and a literature search that examined in-progress and completed domestic and international research about detection systems and technologies.

Survey of Practice

An online survey distributed to members of the Transportation Research Board (TRB) Geology and Geotechnical Engineering Section and members of the American Association of State Highway and Transportation Officials (AASHTO) Committee on Transportation System Operations sought information about the use of early detection, monitoring and alerting best management practices and technology for landslides, rockfalls and other natural hazards that occur in remote areas where telecommunications is absent. Select committee chairs from the TRB Technical Activities Division also received the survey.

Eight state transportation agency representatives and one consultant responded to the survey:

State Transportation Agencies

- Illinois DOT (IDOT)
- Louisiana Department of Transportation and Development (LaDOTD)
- Michigan DOT (MDOT)
- Montana DOT (MDT)
- New Jersey DOT (NJDOT)

- Ohio DOT (ODOT)
- Washington State DOT (WSDOT)
- Wyoming DOT (WYDOT)

Consultant

- Landslide Technology (Cornforth Consultants, Inc.)

Survey questions are provided in Appendix A. Survey results are summarized below in two topic areas:

- Agencies with experience using early warning practices and systems.
- Agencies with no experience using early warning practices and systems.

Agencies with Experience Using Early Warning Practices and Systems

Three state transportation agencies — NJDOT, WSDOT and WYDOT — and the consultant reported having experience with early warning systems and practices to detect and monitor landslides, rockfalls and other natural hazards occurring in rural, remote areas.

The WSDOT and WYDOT respondents briefly described the operating processes of their agencies' systems, from detecting movement to sending an alert:

> WSDOT has established thresholds on its monitoring system. When these thresholds are reached, a text message and email are sent to the monitoring units. The Geotech office checks the alert to ensure it is valid and then notifies Maintenance and, if necessary, conducts a site visit.
>
> In Wyoming, access to real-time data allows the Geology Program to monitor conditions. When an alert is issued, notifications are sent to the WYDOT district office, WYDOT maintenance forces and Highway Patrol if action is needed.

The Landslide Technology consultant has experience providing services to DOTs.

NJDOT currently does not use real-time monitoring systems. Instead, the agency conducts manual evaluations and monitors slopes with the potential for failure. NJDOT is working to incorporate new technologies, including unmanned aircraft systems (UAS), lidar and terrestrial lidar, to provide more real-time monitoring and change detection of slopes.

None of the four agencies used these systems in applications related to debris flow, mudslides or wildfire burn scar areas. WSDOT monitors one rockfall fence using a Geobrugg monitoring product. The agency has also used total stations on rock cuts as they were being constructed. The remainder of its instrumentation is used on landslides. WYDOT monitors slope stability on a temporary basis for construction activities and traffic detours.

Detailed information about these systems and practices is presented below in six categories:

- Detection and monitoring methods.
- System features.
- Slide behavior assessment.
- Data collection.
- Alerts and notifications.
- System assessment.

Detection and Monitoring Methods

These agencies have implemented multiple methods to detect and monitor land movement, including:

- Lidar.
- Network of weather stations and radio systems.
- Remote sensing techniques (such as satellite radar images).
- Scanning radar systems.
- Surveying and sensing instrumentation.
- Video cameras.

All four agencies responding to the survey use remote sensing techniques, and three agencies use lidar and surveying and sensing instrumentation. None of the agencies reported using distributed acoustic sensing (DAS). WSDOT also uses or has used tilt meters, GPS units, total stations, automated piezometers, automated inclinometers (shape arrays), rain gauges, photogrammetry and lasers. Table 1 summarizes survey responses.

Table 1. Types of Detection and Monitoring Methods Used

Agency	Lidar	Weather Station/ Radio Network	Remote Sensing	Scanning Radar Systems	Surveying/ Sensing	Video Camera	Other
New Jersey	X		X				
Washington	X	X	X	X	X	X	Tilt meters, GPS units, total stations, automated piezometers and inclinometers (shape arrays), rain gauges, photogrammetry and lasers.
Wyoming			X	X	X		
Landslide Technology	X	X	X		X	X	
Total	**3**	**2**	**4**	**2**	**3**	**2**	

System Features

Survey respondents provided significant detail about agency systems, including the name of the products used; vendors and manufacturers that provide these products; and costs associated with the systems, both initial cost incurred and the cost of ongoing operations and maintenance. Below are summaries of each agency's systems. The References section following these summaries provides links to the websites of vendors noted by survey respondents.

New Jersey Department of Transportation

Topic	Description
Products	ArcGIS lidar layers
Vendors	Esri
Initial cost	N/A
Ongoing cost	N/A

Washington State Department of Transportation

Topic	Description
Products	• InSAR (interferometric synthetic aperture radar) satellite monitoring (see Related Resources below) • Tilt meters, GPS units, total stations, automated piezometers and inclinometers (shape arrays), rain gauges, photogrammetry and lasers
Vendors	• Geoprobe • Navstar • Senceive • Sensemetrics • Sixense
Initial cost	**Shape Arrays:** Initially expensive. Monitoring fees: $1,000-$2,000/month. **GPS:** Initially: approximately $25,000. Monitoring fees: $1,000-$2,000/month. **Tiltmeters, lasers and cameras:** Approximately $25,000. Monitoring fees: $1,000-$2,000/month. **Geoprobe**: Approximately $250,000 for a few months.
Ongoing cost	Usually approximately $1,000-$2,000/site/month.

Wyoming Department of Transportation

Topic	Description
Products	• InSAR satellite monitoring (see Related Resources below) • Ground-based radar, shape array inclinometer, level logger groundwater monitoring

Topic	Description
Vendors	**Ground-based radar**: • IDS Georadar • AssetAssurance Monitoring, LLC **Satellite monitoring**: KorrAI InSAR **Shape array**: Measurand (Terra Insights for general coordination, RST Instruments for remote login and communication) **Groundwater monitoring**: Solinst
Initial cost	IDS Georadar, KorrAI InSAR satellite monitoring, including AssetAssurance Monitoring, LLC: $192,000 for six months of service, including monthly subscription fees, equipment rental and continuous monitoring. Measurand shape array: $28,000. Solinst groundwater: $2,600.
Ongoing cost	Solinst cloud-based: $4/month. Shape array cloud-based: $100/month. (See **Initial cost** for lump sum cost, including ongoing costs for ground-based radar and satellite InSAR data.)

Landslide Technology

Topic	Description
Products	• **Lidar**: Public accessible or client-obtained lidar/scanning data • **Weather and radio**: Public NOAA (National Oceanic and Atmospheric Administration) weather stations or project-specific weather stations or rain gauges • **Remote sensing** • **Satellite images** or unmanned aerial vehicle (UAV) derived photogrammetry with temporal variability • **Surveying and sensing**: Repeat control point surveys and laser scanning • **Direct sensors** of inclinometers, piezometers, various deformation sensors • **Video cameras**: Data logger-connected cameras
Vendors	• Campbell Scientific • Geokon • Measurerand • RST Instruments • Worldsensing
Initial cost	Varies depending on system configuration

Topic	Description
Ongoing cost	Typically, once-annual site visits to maintain system: approximately $5,000-$15,000.

Related Resources

InSAR—Satellite-Based Technique Captures Overall Deformation "Picture," Volcano Hazards Program, U.S. Geological Survey, undated.
https://www.usgs.gov/programs/VHP/insar-satellite-based-technique-captures-overall-deformation-picture
This tool "detect[s], measure[s], and monitor[s] subtle changes in the shape or relative position of the Earth's surface. By bouncing signals from a radar satellite off the ground in successive orbits and looking at the differences between the images, interferometric synthetic aperture radar (InSAR) can detect small differences in the distance between its position and the ground as the land surface moves — whether up, down or sideways. InSAR shows spatial patterns of deformation in remarkable detail and, in combination with ground-based monitoring, gives USGS [U.S. Geological Survey] scientists unprecedented insight into a wide range of earth science processes."

Monitoring Ground Deformation from Space, U.S. Geological Survey, Fact Sheet 2005-3025, July 2005.
https://pubs.usgs.gov/fs/2005/3025/2005-3025.pdf
This fact sheet explains operation of InSAR and describes its use in monitoring earthquake and volcano activity.

References

AssetAssurance Monitoring, LLC,
https://sites.google.com/aamonitoring.net/assetassurancemonitoring/home.

Campbell Scientific, https://www.campbellsci.com/.

Esri: GIS Software for Mapping and Spatial Analytics, https://www.esri.com/en-us/home.

Geoprobe Systems, https://geoprobe.com/direct-image.

IDS Georadar, https://idsgeoradar.com/applications/geology-and-environment.

KorrAI InSAR, https://www.korrai.com/.

Measurand, https://measurand.com/.

Navstar, https://navstar.com/products/software/in-place-inclinometers/.

Senceive, https://www.senceive.com/.

Sensemetrics, https://www.bentley.com/software/sensemetrics/.

Sixense, https://www.sixense-group.com/en/offer/monitoring/natural-hazards.

Solinst, https://www.solinst.com/.

Worldsensing, https://www.worldsensing.com/.

Slide Behavior Assessment

A number of factors may be monitored to assess slide behavior and forecast a potential slide, including:

- Environmental variables.
- Ground vibrations.
- Pore water pressure development.
- Seepage patterns.
- Terrain characteristics.
- Water content.

Agencies participating in the survey most frequently monitor terrain characteristics (four responses), followed by environmental variables (three responses). In addition to these factors, WSDOT observes subsurface movement with inclinometers and surface deformation with change analysis from terrestrial lidar or airborne lidar/point cloud data, WYDOT supplements conventional instrumentation by monitoring temporary excavation and slope movements, and Landslide Technology has monitored displacement rate.

Seepage patterns and water content are the least likely factors to be monitored (one response each). None of the agencies monitor ground vibrations. Table 2 summarizes survey results.

Table 2. Factors Observed in Slide Monitoring

Agency	Environmental Variables	Pore Water Pressure Development	Seepage Patterns	Terrain Characteristics	Water Content	Other
New Jersey	X		X	X		
Washington	X	X		X		X
Wyoming				X	X	X
Landslide Technology	X	X		X		X
Total	**3**	**2**	**1**	**4**	**1**	**3**

Data Collection

Instrumentation and proprietary practices are typically used to collect data. Transmission occurs through radio and cellular technology. Below is a brief description of each agency's practices:

NJDOT collects raw data, but there are limited post-processing capabilities with the data. The agency is currently evaluating ways to improve these capabilities so it can use the data.

WSDOT uses instrumentation to collect data and transfer it through radio signals to a nearby gateway. The data is then transmitted through cell towers or satellites back to a server, where it is served over the web through an internet browser.

In Wyoming, AssetAssurance Monitoring provides continual monitoring and alerts. Data is accessed through proprietary software for real-time monitoring. Inclinometer and level loggers are shared through a cloud-based subscription. Data gathered through site collection is transmitted through various communication devices such as the internet and satellite communications.

Landslide Technology collects data through radio and cellular technology, site visits and manual collection methods.

Alerts and Notifications

To provide a more comprehensive view of alerting and notification practices, the survey respondents described which organizations or entities within their agencies receive alerts, how the alerts are delivered, how the traveling public is notified of a hazard incident or road closure, and whether the notification to the public is an automated or manual process.

Receiving Alerts

Maintenance operations at NJDOT, WSDOT and WYDOT receive alerts from early warning systems. Other units that receive alerts:

- Internal NJDOT staff in geotechnical engineering and geology, operations and emergency management (if there is a mass movement event).
- Washington's State Geotechnical Office.
- WYDOT's district office, Geology Program and Highway Patrol.

At Landslide Technology, consultants receive the alerts. None of the agencies participating in the survey send alerts to TMCs.

Delivering Alerts

Multiple alert delivery practices are used by WSDOT, WYDOT and Landslide Technology. These organizations send alerts by email and by SMS (Short Message Service) text messaging service. WSDOT and WYDOT also send alerts by telephone. NJDOT hasn't established a system for sending alerts related to land subsidence. Currently the data is collected during field inspections and evaluated at the office.

Notifying the Traveling Public

Three respondents described their agencies' process for alerting the public about a hazard incident or road closure. When a mass movement event occurs in New Jersey, NJDOT informs the public through media and news alerts along with road signage. In Washington, the State Geotechnical Office or WSDOT Maintenance conducts a site visit to assess road conditions and closes the highway if conditions warrant. WYDOT provides travel alerts through the WYDOT TMC notification system, which includes a website and variable message signs (VMS). The agency also has a process to inform district maintenance offices and Highway Patrol if actions are needed.

None of the survey respondents reported actuating a flashing beacon, generating an audio-visual alarm or posting a notice to the 511 real-time traveler information service.

To notify the public about a road closure caused by a slide, NJDOT, WSDOT and WYDOT use a manual process that requires intervention from an operator.

System Assessment

Benefits of an Early Warning System

Three respondents described the benefits of using an early warning system. The Landslide Technology respondent noted the value of data for making informed decisions and identifying appropriate mitigation and risk reduction activities. The WYDOT respondent also noted the value of real-time data to supplement analyses, which enhances the safety of the traveling public and agency staff.

The WSDOT respondent cited the cost-efficiency of systems that are "dialed in," noting the dollars saved throughout the process — from site visits to data collection. These systems also allow agencies to pinpoint movement to weather events and groundwater elevations, and warn agencies that a potential problem is developing.

Challenges of an Early Warning System

Respondents also reported a range of barriers that their agencies have faced with early warning systems and practices. WSDOT often requires additional solar panels and batteries to meet system operation needs. Some systems also need cellular coverage, which is not available in all remote areas where landslides are located. Vandalism and equipment theft are additional issues.

The WYDOT respondent noted that initial challenges included acquiring communication devices to transmit data. Other obstacles include logistical challenges with high-altitude, mountainous terrain; accessing equipment during winter weather; and maintaining battery levels charged through solar panels.

As NJDOT prepares to use real-time monitoring systems, the agency faces challenges with system funding, implementation and management, and staff training.

Related Research

Below are documents provided by survey respondents associated with their use of slide detection, monitoring and alerting best management practices and technology.

National Resources

Landslides: Investigation and Mitigation, Transportation Research Board Special Report, Issue 247, 1996.
http://onlinepubs.trb.org/Onlinepubs/sr/sr247/sr247.pdf
Citation at https://trid.trb.org/View/462498
Recommended by the NJDOT respondent, this resource is an update of the 1978 edition and continues to be a valuable reference for issues related to rock slope design. In 2016, the Rockfall Management subcommittee of the TRB Standing Committee on Engineering Geology surveyed practitioners and found "that 61 percent of the respondents use *TRB Special Report 247—Landslides: Investigation and Mitigation* as a reference for rock slope design and as design guidelines. That same survey also indicated that 71 percent also use the TRB's *Rockfall: Characterization and Control*, published in 2012, as a reference for rockfall design." *From the report citation*:

> The new report, which has been designed with an even broader international scope, contains comprehensive, practical discussions of field investigations, laboratory testing and stability analysis procedures and technologies; comprehensive references to the literature; and discussions of case studies, state-of-the-art techniques and research directions.

Related Resource:

Rockfall: Characterization and Control, Transportation Research Board, 2012.
Citation at https://trid.trb.org/View/1244049
From the abstract: Demands for improved rockfall evaluation and mitigation have encouraged adoption of new technologies to support new approaches to the evaluation and quantification of rockfall hazards and the provision of protection from rockfalls. … The book addresses the state of knowledge about rockfall, the available procedures for rockfall investigation, and the regulatory and economic climates affecting rockfall investigations and corrective actions.

State Resources

Montana

MDT Highway 135 Rock Slope Monitoring, Montana Department of Transportation, undated.
https://app.konectgds.com/kiosk/0e26afbc-f26c-43a2-997a-62b23f9f0f99
Landslide Technology developed this web page for rock slope monitoring for Montana DOT. Gauges from the up-station, middle and down-station crackmeters indicate total displacement and alarm movement, which "is defined as having 5 mm or more displacement greater than a 24-hour movement average. An alarm notification will be triggered to send an email if this movement threshold is exceeded." The web page provides a seven-, 30- and 180-day history; configuration of crackmeters and enclosures; a map of station locations; battery voltage; and panel temperature.

Related Resources

"Landslide Detection, Monitoring and Prediction with Remote-Sensing Techniques," Nicola Casagli, Emanuele Intrieri, Veronica Tofani, Giovanni Gigli and Federico Raspini, *Nature Reviews Earth and Environment*, Issue 4, pages 51-64, 2023.
Citation at https://www.nature.com/articles/s43017-022-00373-x
From the abstract: In this Technical Review, we describe the use of RSTs [remote-sensing techniques] in landslide analysis and management. Satellite RSTs are used to detect and measure landslide displacement, providing a synoptic view over various spatiotemporal scales. Ground-based sensors (including ground-based interferometric radar, Doppler radar and lidar) monitor smaller areas, but combine accuracy, high acquisition frequency and configuration flexibility, and are therefore increasingly used in real-time monitoring and early warning of landslides. Each RST has advantages and limitations that depend on the application (detection, monitoring or prediction), the size of the area of concern, the type of landslide, deformation pattern and risks posed by landslide. The integration of various technologies is, therefore, often best. More effective landslide risk management requires greater leveraging of big data, more strategic use of monitoring resources and better communication with residents of landslide-prone areas.

Agencies with No Experience Using Early Warning Practices and Systems

Transportation agencies in five states — Illinois, Louisiana, Michigan, Montana and Ohio — do not use detection, monitoring and alerting best management practices and technology for landslides, rockfalls and other natural hazards occurring in rural, remote areas. No equipment is currently installed in Illinois. The IDOT respondent noted that only minor issues have occurred in one area of the state.

Two other DOT representatives described efforts underway at their agencies:

Louisiana. LaDOTD would like to initiate a research project to begin geotechnical asset management for slopes and embankments soon. The respondent noted that Louisiana is a relatively flat state, with limited elevation changes. Most embankments are man-made and located in urban or suburban areas of the transportation network.

Michigan. MDOT does not have slide detection, but the respondent provided information about weather features that may be of interest to Caltrans. MDOT monitors bridge deck and icy road conditions in multiple areas of the northern portion of the state's Lower Peninsula. Noninvasive pavement sensors used at Environmental Sensor Stations (ESS) activate a warning sign to alert drivers when certain pavement conditions are met. The biggest factors at these locations are temperature, precipitation and surface friction.

On Interstate 94 (I-94) in southwest Michigan, an area that receives a lot of lake effect snow, a variable speed advisory system is connected to the agency's advanced traffic management system (ATMS). ESS devices collect air temperature, humidity, precipitation rate and other weather data and allow auto-response plans created in ATMS to send messages to DMS along the corridor. Agency operators confirm if the correct message is displaying and can make adjustments or override the message if necessary. Some locations have closed-circuit television (CCTV) or microwave vehicle detection systems (MVDS) along with the ESS devices. Essentially, if certain criteria are met, the agency can notify drivers of conditions and advise them to slow down. To ensure drivers receive accurate information, each device along the corridor operates independently because the weather in the region can vary significantly.

Consultation with Experts

Select Caltrans districts and university partners were contacted to gather information about pilot projects and research underway in California. Below are summaries of those efforts.

District 2

Contacts: Andre Chavez, Project Manager, Senior Transportation Electrical Engineer/Specialist, Rural ITS and Special Projects Research, California Department of Transportation, 530-306-7985, andres.chavez@dot.ca.gov.

Jeremiah Pearce, Chief, Office of ITS Engineering and Support, District 2, California Department of Transportation, 530-225-3320, jeremiah.pearce@dot.ca.gov.

Dinesh Kumar, Research and Development Engineer 2, University of California, Davis College of Engineering, 530-752-7990, dskumar@ucdavis.edu.

District 2 is partnering with the University of California, Davis in a pilot evaluation using DAS technology for vehicle detection and monitoring in transportation management. The pilot only recently got underway (launched October 17, 2024); technologies have not yet been deployed in the field, and research data is not yet available.

District 5

Contact: Ryan Turner, Senior Transportation Engineer Specialist, California Department of Transportation, 805-748-1706, ryan.turner@dot.ca.gov.

A rock slide construction project is underway at Regent's Slide along Highway 1 following a hillside collapse. Repairs and monitoring are ongoing in this corridor.

Remote monitoring equipment used at the site includes a prism in a total station survey (Trimble T4D Control hardware and software) and daily UAS flights that monitor displacement and changing site conditions (cut and fill volume). In-ground monitoring equipment includes shape arrays and vibrating wire piezometers to detect groundwater and ground movement. Vista Data Vision (VDV) is used to process the sensor data. This visualization platform presents raw data as plots of displacement and groundwater elevations. The base station also includes solar arrays and batteries for power and Starlink internet service to transmit data.

Displacement, groundwater elevation and change detection are the key factors monitored, with displacement as the focus. Additional data is collected about the health of the monitoring systems. The datastream is checked daily (manually). Information is integrated with other data to inform decisions about safety and construction project activities.

Some of the equipment used in this repair has been repurposed from other projects, including the 2018 Mud Creek project, making it difficult to estimate the cost of the technologies. A ballpark estimate is $200,000 upfront and $100,000 annually for operations.

Turner noted that remote sensing is not automated. Systems need uninterrupted power and internet service to collect data, which can be difficult to maintain. Adverse weather and other events can interrupt these services, causing a lapse in data collection and requiring human intervention to repair.

References

Trimble 4D Control (T4D), https://geospatial.trimble.com/en/products/software/trimble-4d-control.

Vista Data Vision by Bentley Systems (VDV), https://www.bentley.com/software/vista-data-vision/.

District 10

Contacts: Arlene Cordero, Chief, ITS Operations Branch, California Department of Transportation, 209-948-7449, arlene.cordero@dot.ca.gov.

Corey Casey, Project Manager, Ferguson Rock Shed Project, California Department of Transportation, 209-607-8789, corey.casey@dot.ca.gov.

Corey Casey, the project manager, provided two project documents that were used to prepare this project summary: Geotechnical Instrumentation Installation and Manually Collected Data, and Site Specific Safety Plan and Fire Prevention Plan. These documents have been provided to Caltrans separately.

The purpose of the Ferguson Rock Shed Project is to restore access to State Route 140 in Mariposa County by building a protective rock shed structure at the site.

To monitor the rock slide during construction, geotechnical instrumentation has been installed at four monitoring stations. Subsurface instruments, including vibrating wire piezometers, shape accelerometer arrays and time domain reflectometry sensors, monitor groundwater levels and subsurface deformation. An automatic data collection and transmission system, including data loggers, weather instruments (rain gauges, thermistors and barometers), sensor interfaces and radio telemetry system, monitors the sensors in near real time. The equipment uses an existing data link (wireless Ethernet bridge) to transmit subsurface monitoring data to the internet.

The automated monitoring systems are programmed to record data at one-hour intervals at all four stations. Data is then stored locally on data loggers and transmitted via radio link hourly to the internet. VDV servers store and process the data, allowing users to access the data in near real time.

Related Research and Resources

A literature search of publicly available domestic and international in-progress and published research sought information about early slide detection, monitoring and alerting best practices and technologies, and the performance and effectiveness of those systems. Resources identified in this search are presented in two categories:

- Highways.
- Railways.

Within each of these categories, citations are further organized according to national, state and international research and resources.

Highways

National Research and Resources

Resources from the U.S. Geological Survey are presented in this section, including a reference to the newly formed National Landslide Hazard Risk Reduction (NLHRR) working group.

National Landslide Hazard Risk Reduction Working Group, National Hazards Program, U.S. Geological Survey, undated.
https://www.usgs.gov/programs/landslide-hazards/national-landslide-hazards-risk-reduction-working-group
The NLHRR working group, supported by the U.S. Geological Survey Landslide Hazards Program, was established "to share best practice methods, develop collaborations, enhance communication, enable training opportunities and inspire the co-creation of new initiatives." The group originated as part of the *National Strategy for Landslide Loss Reduction*, which "[outlines] the goals and strategic activities to facilitate implementation of the National Landslide Preparedness Act." The web page presents information about this newly formed working group, including:

- Details about the membership.
- Goals of the group:
  - **Share ideas and methods**: standardizing methods; planning and response; addressing data gaps; overcoming barriers; sharing lessons learned; and collaborating on regional, topical, workplace ecosystems.
  - **Conduct trainings**: mapping, inventorying and schema; thresholds and warnings; geophysical techniques; product, needs and risk assessments; communication, education and engagement.
  - **Engage in collective creation**: annual proceedings document, national map and inventory contributions, database of methods and guide for mitigation planning.
- **Potential timeline and structure of the group.** The group held its first meeting virtually November 14, 2024. Regular monthly virtual meetings were scheduled to begin in January 2025. Group members anticipate forming interest groups based on members' interests and initiatives and taking on related tasks or projects.

Contacts:

Sarah Hall, AAAS Science and Technology Policy Fellow, Landslide Hazards Program, U.S. Geological Survey, srhall@usgs.gov.

Stephen Slaughter, Associate Program Coordinator, Landslide Hazards Program, U.S. Geological Survey, sslaughter@usgs.gov, 303-273-8482.

Related Resources:

National Strategy for Landslide Loss Reduction, Jonathan W. Godt, Nathan J. Wood, Alice Pennaz, Connor M. Dacey, Benjamin B. Mirus, Lauren N. Schaefer and Stephen L. Slaughter, U.S. Geological Survey, 2022.
Citation at https://www.usgs.gov/publications/national-strategy-landslide-loss-reduction
Report at https://pubs.usgs.gov/of/2022/1075/ofr20221075.pdf
From the executive summary:

> This strategy document will provide a framework for the creation of an interagency management plan that describes the programs, projects, workforce and budgets required to carry out the national strategy. … The strategy outlined in this document presents a vision of how to equitably produce, communicate, and apply landslide data and science to support a broad range of land management, infrastructure, planning, and emergency response decisions. These decisions are made by a variety of actors, including private and nonprofit landholders; [s]tate, [t]ribal, territorial, city and county planners; emergency managers; engineers; infrastructure managers; [f]ederal agencies and their partners; and community leaders and individuals. Supporting those decisions and reducing the [n]ation's vulnerability to landslides requires overcoming three main challenges: (1) gaps in basic information needed to describe and understand landslide occurrence and societal risk, (2) difficulty in accurately mapping and forecasting landslide hazards, and (3) communication and coordination among the many jurisdictions and sectors that have responsibility for and interest in reducing landslide losses.

Strategic Action 2.4 of the Coordination Goal recommends that an NLHRR working group be established and supported (page 22 of the report; page 32 of the PDF).

Landslide Hazards Program, U.S. Geological Survey, undated.
https://www.usgs.gov/programs/landslide-hazards
From the website: The primary objective of the [n]ational Landslide Hazards Program is to reduce long-term losses from landslide hazards by improving our understanding of the causes of ground failure and suggesting mitigation strategies.

State Research and Resources

Citations in this section address the installation of a ground monitoring system in a remote area of Colorado with poor cellular reception following a 2013 incident; a project in Hawaii that integrated a model into the DisasterAWARE platform, which provides early warning and risk assessment services for 19 different types of natural hazards and has a mobile app that can create and send regional hazard alerts to its users; and a proposed project in Oregon to install monitoring and alerting sensors for a variety of applications, including landslide warning and detection systems in key transportation corridors.

Colorado

Shannon & Wilson's State-of-the-Art Monitoring System Prevents Flooding on Colorado's US 36, Bentley Advancing Infrastructure, 2023.
https://www.infrastructureiot.com/wp-content/uploads/2023/01/CaseStudy_sensemetrics_CDOT.pdf
From the project summary:

Project Objectives

- To continually monitor a remote area of highway subject to rockfall.
- To establish a cost-effective system that can provide alerts based on real-time sensor data.

Fast Facts

- In 2013, historic rainfall and flooding caused USD 2 billion in property loss and extensive damage to Colorado infrastructure, including roads.
- Damage caused to US Highway 36, a key artery for tourists, trucks and local traffic, was repaired but the road remained subject to rockfall caused by erosion.
- Shannon & Wilson needed to improve ground monitoring in a remote area with poor cellular reception while using legacy sensors.

Return on Investment

- The continual data provided by sensemetrics [sensors] has improved safety and enhanced asset management along US 36.
- Data from the sensors provide a longer-term picture to understand ground and rock movements, helping prevent damage and ensure safety.

Hawaii

NASA Partners with Pacific Disaster Center on New Landslide Hazard Assessment and Warning System, Geoengineer.org, October 26, 2023.
https://www.geoengineer.org/news/nasa-partners-with-pacific-disaster-center-on-new-landslide-hazard-assessment-and-warning-system
From the website: A collaboration between NASA and University of Hawaii's Pacific Disaster Center (PDC) was recently made public on October 26, regarding NASA's Landslide Hazard Assessment for Situational Awareness model (LHASA) and PDC's DisasterAWARE.

Furthermore, NASA spent years on the development and testing of LHASA, an open-source machine learning model that was trained by a database of historical landslides, including the environmental conditions surrounding them. This model is capable of recognizing the likelihood of a landslide occurring, based on location, environmental data and near real-time precipitation monitoring from NASA's IMERG [Integrated Multi-satellitE Retrievals for GPM [Global Precipitation Measurement]].
….

Partnering with PDC, this model was integrated into the DisasterAWARE platform, which provides early warning and risk assessment services for 19 different types of natural hazards.

This way, LHASA's data is mapped on the platform and can help decision-makers assess landslide risks quickly and effectively. In addition to this, DisasterAWARE's mobile app can create and send regional hazard alerts to its users.

Finally, the platform is also capable of providing regional risk reports regarding the number of people and infrastructure exposed to the disaster, so that effective remediation or prevention plans can be taken accordingly by decision-makers worldwide.

Oregon

Research in Progress: The Willamette Watershed Project: A Resilient Communications, Monitoring and Alerting Network for the Willamette Valley, Oregon Hazards Lab, University of Oregon, undated.
Project description: https://ohaz.uoregon.edu/willamette-watershed-project/
Oregon Hazards Lab: https://ohaz.uoregon.edu/
The goal of this project is to "lay new communications infrastructure, including a new backbone network of fiber cables and a network of fixed wireless sensors." Monitoring and alerting sensors will be installed for a variety of applications, including landslide warning and detection systems in key transportation corridors. According to the website, this project was in the early stages of development in July 2022:

> Currently, the Oregon Hazards Lab is researching and planning for the construction of new fiber cables and integrated multi-hazards sensors. It is also developing a cost-benefit analysis for future projects and identifying and applying for grants. It has also begun coordinated stakeholder engagement in the project area.

Pennsylvania

Artificial Intelligence (AI) for Building a Landslide Inventory and Advanced Landslide Warning System in PA, Tong Qiu and Jun Xiong, Pennsylvania Department of Transportation, August 3, 2023.
https://www.pa.gov/content/dam/copapwp-pagov/en/penndot/documents/research-planning-innovation/research-projects/artificial%20intelligence.pdf
From the abstract: This report presents the results of a study aiming at developing artificial intelligence (AI) models for advanced warning of rainfall induced landslides for unstable slopes above or below state-maintained roadways in Pennsylvania. Two landslide databases for spatial and spatiotemporal analyses of landslides in Pennsylvania and adjacent areas are compiled. Landslide susceptibility maps (LSMs) are generated for PennDOT Districts 11 and 12 and adjacent areas, including northern West Virginia and eastern Ohio. The results indicate that the spatiotemporal machine learning (ML) model can predict landslides, accounting for both spatial terrain factors and temporal rainfall factors, and the model outperforms pure spatial ML models with the same database size. The LSMs generated from this study highlight areas having very low to very high risk of landslide susceptibility with precipitation, which may be used to establish a hierarchy and mitigate risk for slopes at "very high risk" for landslide susceptibility. The maps may also be used for forecasting purposes. For example, they may be used as an aid for planning and programming purposes to address slopes with "very high" landslide susceptibility first. The maps may be used in the event of incoming storms to target slopes with a very high risk of landslide susceptibility so that mitigation or preventative measures (such as temporary road closure) can be employed to ensure safe travel and minimize damage. In addition, the maps may also help to target post-storm roadway/slope inspections to the most critical and high-risk locations first.

International Research and Resources

Citations in this section include a 2025 journal article about a high-resolution monitoring system installed at a site in southern Italy that enables timely road closure to traffic in case of another rockfall; a 2024 journal article about a project in Italy where Doppler radar was programmed to actuate a pair of traffic lights so that a predefined exclusion zone could instantly be enforced for approaching vehicles upon initial slide movement detection; and a 2017 conference paper about a remote monitoring system in Manitoba that detects activity from slow-moving landslides and provides early warnings of dangerous road conditions by sending text messages and email alerts to notify department maintenance staff of abnormal landslide movements. Also included are a 2018 journal article about the development of an advanced slope disaster monitoring system for practical use on expressways in Japan and a 2019 inventory of global early warning systems that identifies the type of landslide monitored and the most used monitoring parameters and instruments for issuing warnings.

Multiple Continents

"Monitoring Strategies for Local Landslide Early Warning Systems," Gaetano Pecoraro, Michele Calvello and Luca Piciullo, *Landslides*, Vol. 16, pages 213-231, 2019.
Citation at https://link.springer.com/article/10.1007/s10346-018-1068-z
From the abstract: The main aim of this study is the description and the analysis of the monitoring strategies implemented within local landslide early warning systems (Lo-LEWS) operational all around the world. Relevant information on 29 Lo-LEWS [has] been retrieved from peer-reviewed articles published in scientific journals and proceedings of technical conferences, books, reports and institutional web pages. The first part of the paper describes the characteristics of these early warning systems considering their different components. The main characteristics of each system are summarized using tables with the aim of providing easily accessible information for technicians, experts and stakeholders involved in the design and operation of Lo-LEWSs. The second part of the paper describes the monitoring networks adopted within the considered systems. Monitoring strategies are classified in terms of monitored activities and methods detailing the parameters and instruments adopted. The latter are classified as a function of the type of landslide being monitored. The discussion focuses on issues relevant for early warning, including appropriateness of the measurements, redundancy of monitoring methods, data analysis and performance. Moreover, a description of the most used monitoring parameters and instruments for issuing warnings is presented.

Asia

"Monitoring Slow-Moving Deep-Seated Landslide Using PSI Technique: A Case Study of a Potential Sliding Slope from Southern Taiwan," Abhishek Lakhote, Yu-Chang Chan, Chiao-Yin Lu, Gopal Kumar and Cheng-Wei Sun, *Landslides*, 2025 (published online).
https://link.springer.com/content/pdf/10.1007/s10346-024-02453-z.pdf
From the abstract: Studying slow-moving, deep-seated landslides is crucial due to their long-lasting effects on landscapes, infrastructure and communities. In mountainous regions like Taiwan, understanding these landslides is vital for hazard mitigation and land-use planning. Over 2,500 pre-existing landslides have been cataloged in Taiwan using LiDAR data, with many identified as potential slow-moving landslide zones, including a significant site, the Liugui-D047, near Hsinfa Village in southern Taiwan. This study aims to understand the E-W [east-west] and vertical deformation rates at the potential landslide site using the persistent scattering interferometry (PSI) technique. PSI is particularly effective for detecting slow-moving landslides, providing millimeter-level precision in surface deformation measurements over time. By utilizing open-source tools like ISCE and StaMPS, we conducted a five-year PSI analysis from 2018 to 2023 to monitor surface movements at the site. Our results revealed minimal deformation rates, with westward movements ranging from 4.1 to 2.2 mm/[year] and vertical downward movements from 4.2 to 1.4 mm/[year]. These findings were validated by in situ measurements collected in 2023, confirming the observations of PSI for long-term monitoring. This highlights the effectiveness of combining PSI techniques with open-source tools for monitoring landslide sites, especially in areas with limited in-situ resources. Our study shows that this integration can yield detailed, long-term insights into surface deformations while reducing the costs of extensive in-situ monitoring.

"Entering the Era of Earth Observation-Based Landslide Warning Systems: A Novel and Exciting Framework," Keren Dai, Zhenhong Li, Qiang Xu, Roland Bürgmann, David G. Milledge, Roberto Tomás, Xuanmei Fan, Chaoying Zhao, Xiaojie Liu, Jianbing Peng, Qin Zhang, Zheng Wang, Tengteng Qu, Chaoyang He, Deren Li and Jingnan Liu, *IEEE Geoscience and Remote Sensing*, Vol. 8, Issue 1, pages 136-153, March 2020.
Citation at https://ieeexplore.ieee.org/document/8994058
From the abstract: In this article, we use two recent landslides in China as case studies to demonstrate that satellite radar observations can be used to detect deformation precursors to catastrophic landslides and that early warnings can be achieved with real-time, in situ observations. We propose a novel and exciting framework that employs EO [Earth observation] technologies to build an operational landslide EWS [early warning system].

"Development of a Slope Disaster Monitoring System for Expressway Operation and Maintenance Control," Keiji Sakuradani, Keigo Koizumi, Kazuhiro Od and Satoshi Tayama, *Journal of GeoEngineering*, Vol. 13, No. 4, pages 189-195, December 2018.
http://140.118.105.174/jge/files/articlefiles/v13i420190122805742969.pdf
From the abstract: This paper reports on the development of an advanced slope disaster monitoring system for practical use on expressways in Japan. Owing to a rise in unexpected heavy rainfall events, the incidence of rain-induced slope failure is increasing in Japan. To address this problem, the West Nippon Expressway Company Ltd. (W-NEXCO), in addition to its responsibility for monitoring the health of aging civil structures, is tasked with the real-time monitoring of rain-induced slope failure, has developed, in cooperation with Osaka University, a user-friendly slope disaster monitoring system based on an ad hoc, multi-hop sensing technology. This monitoring system, called a mesh network, comprises monitoring stations using the W-NEXCO private network and multiple sensor nodes. The monitoring stations are powered by rechargeable batteries with solar panels, while the sensor nodes are primarily battery-driven. Correspondingly, AC power supply is not necessary at the monitoring sites. The sensor nodes enable multi-sensing functionality for monitoring anchor axial force, ground surface displacement, water level, pore water pressure, rain intensity, volumetric water content, and feature contact output channels for activating warning signal lamps. In this manner, the sensor nodes are useful not only for monitoring slope failure but also for signaling the need for slope maintenance via a ground anchor and embankment drainage evaluation. W-NEXCO is placing wireless local area network (WLAN) access points along expressways to allow for the rapid and stable importing of monitoring data collected from each slope structure into the W-NEXCO private server. In this study, we confirmed the applicability of this system and its WLAN network based on the results of communication tests performed on actual expressway slopes.

"Wireless Sensor Network in Landslide Monitoring System with Remote Data Management," Vu Van Khoa and Shingeru Takayama, *Measurement*, Vol. 118, pages 214-229, March 2018.
Citation at https://www.sciencedirect.com/science/article/abs/pii/S0263224118300022
Highlights:

- A system applying wireless sensor network for monitoring landslide is introduced.
- A data management scheme with structure and data lists is applied to the system.
- Statuses of the field and system elements are monitored remotely through data.

From the abstract: This paper describes a system that uses a wireless sensor network (WSN) to monitor landslide disasters in remote areas. The system consists of [three] subsystems called the [l]ocal [s]ensing [n]ode [n]etwork [s]ystem (LSNNS), the [c]loud [s]ystem (CS), and the [h]ost [s]ystem (HS). To monitor the field status and condition of the nodes remotely, we set up an appropriate management scheme in which the HS collects various data types in categories: node status, node data, LSNNS status and LSNNS data. Equivalent lists are available to manage the HS and CS. Each data type contributes to [one] or [two] key analyses in determining a temporary situation. Experiments are conducted to investigate some featured data for landslide monitoring application, including node posture, dynamic change of topology, landslide occurrence recognition and node location change. Where WSN is a candidate for monitoring natural disasters, this remote management scheme provides the surveillance process with extra information and helps the operator to comprehend the situation and maneuver with less effort.

Europe

"Landslide Monitoring and Maintenance Plan Along Infrastructure: The Example of the Maratea Major Rockfall (Southern Italy)," A. Santo and L. Massaro, *Landslides*, Vol. 22, pages 975-987, 2025.
Citation at https://link.springer.com/article/10.1007/s10346-024-02409-3
From the abstract: On the 30th of November 2022, a major rockfall event occurred in the Triassic dolostones of Castrocucco cliff (Maratea, Southern Italy), destroying the underlying SS18 national road with no fatalities or injuries. Successively, engineering works were applied to allow the restoration of the road, although the construction of a bypass tunnel to avoid the cliff was designed as the ideal solution. Before the tunnel can be completed, the critical importance of the road required its reopening with a high-resolution monitoring system that enables the timely road closure to the traffic in case of new failure. In this study, we describe the data collection and the reconstruction of the rockfall kinematics, as well as the susceptibility analysis carried out for the development of the monitoring system that allowed the reopening of the road. Such methodological approach and workflow could be applied to similar situations where critical road infrastructures lie in areas of high susceptibility to rockfall.

"Innovative Extenso-Inclinometer for Slow-Moving Deep-Seated Landslide Monitoring in an Early Warning Perspective," Emilia Damiano, Magno Battipaglia, Martina de Cristofaro, Settimio Ferlisi, Domenico Guida, Erika Molitierno, Nadia Netti, Mario Valiante and Lucio Olivares, *Journal of Rock Mechanics and Geotechnical Engineering*, November 2024. (In press, corrected proof.)
https://www.sciencedirect.com/science/article/pii/S1674775524005511
From the abstract: In the case of slow-moving deep-seated landslides involving huge areas and characterized by complex patterns, when the cost of repairing infrastructures, relocating communities and restoring cultural sites might be such that it is unsustainable for the community, the exposed structures require significant effort for their surveillance and protection, which can be supported by the development of innovative monitoring systems. For this purpose, a smart extenso-inclinometer, realized by equipping a conventional inclinometer tube with distributed strain and temperature transducers based on optical fiber sensing technology, is presented. In situ monitoring of the active deep-seated San Nicola landslide in Centola (Campania, southern Italy) demonstrated its ability to capture the main features of movements and reconstruct a tridimensional evolution of the landslide pattern, even when the entity of both vertical and horizontal soil strain components is comparable. Although further tests are needed to definitively ascertain the extensometer function of the new device, by interpreting the strain profiles of the landslide body and identifying the achievement of predetermined thresholds, this system could provide a warning of the trigger of a landslide event. The use of the smart extenso-inclinometer within an early warning system for slow-moving landslides holds immense potential for reducing the impact of landslide events.

"Real-Time Detection and Management of Rockfall Hazards by Ground-Based Doppler Radar," Tommaso Carlà, Giovanni Gigli, Luca Lombardi, Massimiliano Nocentini, Lorenz Meier, Lino Schmid, Susanne Wahlen and Nicola Casagli, *Landslides*, Vol. 21, pages 155-163, 2024.
https://link.springer.com/article/10.1007/s10346-023-02144-1
From the abstract: Rockfalls are ubiquitous products of landscape evolution in steep mountainous terrains. Among other effects, they pose a significant concern to the management of transportation corridors located on valley floors. Here, we describe the field application of a ground-based Doppler radar that performs real-time, long-range, wide-area detection and tracking of rockfalls and related slope hazards. We deployed the instrument at the Ruinon landslide, where accelerated deformation of upper chaotic debris has for several months promoted secondary mass wasting processes of extremely rapid velocity. In particular, large rolling boulders had the potential to propagate beyond the toe of the landslide and impact a road that connects important localities in the Italian Alps interiors. The Doppler radar was programmed to actuate a pair of traffic lights so that a predefined exclusion zone could instantly be enforced for approaching vehicles upon initial movement detection. We discuss the setup of the alarm system, the main observations collected during the monitoring campaign, and how this technique may enhance safety in areas critically exposed to rockfalls, as well as our understanding of rockfall dynamics in general.

"Rockfall Early Warning System for Enhancing Traffic Safety," M. Castiglioni, T. Caraffa, C. Ottavi, S. Autuori, C. Pullano, A. Lippolis, C. Mallardo, A. Santo, L. Massaro, E. Marino and A. Brunetti, *New Challenges in Rock Mechanics and Rock Engineering*, 2024.
Citation at https://www.taylorfrancis.com/chapters/edit/10.1201/9781003429234-224/rockfall-early-warning-system-enhancing-traffic-safety-castiglioni-caraffa-ottavi-autuori-pullano-lippolis-mallardo-santo-massaro-marino-brunetti?context=ubx
From the abstract: This article presents a case study of the early warning monitoring system made to prevent or reduce risks in case of rock mass deformation and consequent rockfalls.

A severe rockfall in November 2022 occurred and destroyed part of the national road n. 18 "Tirrena Inferiore" in Southern Italy, [where] surveillance and maintenance are operated by ANAS SpA (Gruppo Fs Italiane), the Italian leading [c]oncessionaire of national road and motorway network. ANAS SpA, in cooperation with other national and local authorities, accomplished to rebuild the road body and to mitigate the hazard. To enhance traffic safety and ensure the functionality of the protection structures, ANAS activated the on-site surveillance and implemented a remote real-time monitoring activity of the slope movement integrated with automatic real-time early warning systems using a software that identifies settlements and/or displacements exceeding the threshold limits and sends an e-mail alert.

"An Innovative Early Warning System for Rockfall Protection Systems and Events," Michael Koutsourais, Luca Gobbin, Alberto Grimod and Sage Evans, *Proceedings of the 72nd Highway Geology Symposium*, pages 528-536, 2023.
https://www.highwaygeologysymposium.org/wp-content/uploads/72nd-HGS-Tacoma-WA-2023-Proceedings_.pdf
From the abstract: The paper describes an innovative alert system developed to verify if a rockfall or debris flow protection system is impacted, or if an event, such as a landslide or rockfall, might happen.

This new alert system, HELLOMAC, is installed directly on the rockfall/debris flow protection structure or on the landslide or unstable rock surface, and an acquisition unit (Hubir) is used to collect the data of up to 100 devices in a radius of 5 km and transmit an alerting message by satellite and/or GPRS [ground penetrating radar services].

The paper describes the alert system in detail and its different applications, and it presents a very interesting installation along SS 34, a major road in northern Italy running alongside Lake Maggiore and connecting the city of Verbania with the Swiss border.

"Long-Term Evolution and Early Warning Strategies for Complex Rockslides by Real-Time Monitoring," G. B. Crosta, F. Agliardi, C. Rivolta, S. Alberti and L. Dei Cas, *Landslides*, Vol. 14, pages 1615-1632, March 2017.
Citation at https://link.springer.com/article/10.1007/s10346-017-0817-8
From the abstract: The potential of long-term, real-time surface displacement monitoring by ground-based radar interferometry (GB-InSAR) to improve the understanding of mechanisms and set up objective early warning criteria for complex rockslides is explored. Monitoring data for a rockslide in the Central Italian Alps, collected since 1997 by ground-based and remote-sensing techniques, are examined. A unique [nine]-year continuous GB-InSAR monitoring activity supported an objective subdivision of the rockslide into "early warning domains" with homogeneous involved material, mechanisms and sensitivity to rainfall inputs. Distributed GB-InSAR data allowed setting up a "virtual monitoring network" by a posteriori selection of critical locations representative of early warning domains, for which we analyzed relationships among rainfall descriptors and displacement rates. The potential of different early warning criteria, depending on the instability mechanisms dominating different domains, is tested. Results show that (a) rainfall intensity-duration-displacement rate relationships can be useful tools to predict displacements of "rainfall-sensitive" rockslide sectors, where clear trigger-response signals occur, but are unsuitable in rockslide domains affected by the long-term progressive failure of the rock slope and (b) effective early warning strategies for collapse scenarios (entire rockslide, specific domains) can be enforced by modelling real-time, high-frequency GB-InSAR data according to the accelerated creep theory.

North America

Remote Monitoring System PTH 83 Shell River Landslide, Russell, Manitoba, S. Alexander and J. Tallin, *2017 Conference of the Transportation Association of Canada*, 2017.
https://www.tac-atc.ca/wp-content/uploads/alexanders-pth_83_shell_river_landslide_remote_monitoring_system.pdf
From the abstract: In November 2015, Manitoba Infrastructure installed a remote monitoring system at the site to detect landslide movements and provide early warnings of dangerous road conditions. The system consists of two laser distance measuring devices (LDM) and a shape accelerometer array (SAA). The LDMs are mounted on the top of the landslide escarpment and measure distances to targets located in the active part of the landslide. The 25 m deep SAA is positioned between the two LDM targets and measures ground movement to the base of the landslide.

Data is collected every hour and sent to Manitoba Infrastructure's Winnipeg office where it is automatically processed and uploaded to a website for viewing. The system was designed to send text message and email alerts to notify department maintenance staff of abnormal landslide movements so they can get to the site and assess the road conditions. This paper presents a background of the landslide, and a description and evaluation of the remote monitoring system.

Railways

National Research and Resources

"Detection of Rockfall-Prone Areas Through InSAR-SBAS Analysis," *Research Results*, Office of Research, Development and Technology, Federal Railroad Administration, September 2024.
https://railroads.fra.dot.gov/sites/fra.dot.gov/files/2024-09/Geohazards%20InSAR-SBAS%20Analysis.pdf
From the summary: This work employs the SBAS [Small Baseline Subset] analysis to identify areas along the railroad ROW [right of way] that exhibit increased geohazard risk. SBAS is implemented within the framework of "threshold stacking" as an efficient method of filtering SBAS data for rockfall risk localization. The research team implemented the proposed technique in two incidents involving rockfalls that resulted in train derailments: the first incident site is in Sandstone, West Virginia, and the second site is in Maupin, Oregon. These two cases validate the proposed approach and demonstrate its effectiveness in identifying high-risk areas prone to failure. Furthermore, the case studies underscore how satellite-based monitoring can enhance early warning systems for geohazards and assist disaster mitigation and preparedness efforts.

International Research and Resources

Citations presented in this section include a 2024 journal article and 2023 conference paper about the potential of seismic-driven near real-time rockfall alarm systems for railway monitoring; a 2023 article from a rail transportation sector news and information service about the use of DAS technology in Sensonic landslide and rockfall alerting systems; and a 2017 journal article about integrating AI in a multisensor monitoring system devoted to rockfall detection.

Asia

"Monitoring and Early Warning Method for a Rockfall Along Railways Based on Vibration Signal Characteristics," Yan Yan, Ting Li, Jie Liu, Wubin Wang and Qian Su, *Scientific Reports*, Vol. 9, 2019.
https://www.nature.com/articles/s41598-019-43146-1
From the abstract: Rockfall disasters occur frequently in mountainous areas of western China, and the rockfall disasters along a railway line will seriously affect the safety and normal operation of railways, causing great economic and property losses. Existing rockfall monitoring and early warning methods still have shortcomings, such as accurate warning of single-point disasters and vulnerability to the natural environment. In this study, a rockfall test of a flexible safety protection net along the slope of a railway and a rockfall test of the railway track were carried out, and the vibration signals of the falling rock hitting the different sites of the protective net and hitting different positions of the rails were obtained. Using the signal analysis methods such as Fast Fourier Transformation and Short-Time Fourier Transform, the basic characteristics of the rockfall vibration signal and the vibration signal when the train passes and the propagation law of the rockfall vibration signal are obtained. Finally, a set of monitoring and early warning systems for rockfall disasters along the railway based on the analysis of vibration signal characteristics is established. The monitoring and early warning method has the advantages of all-weather, high-time, semi-automatic and high-efficiency performance.

Europe

"Rockfall Alarm System for Railway Monitoring: Integrating Seismic Detection, Localization and Characterization," Théo Rebert, Caifang Cai, Amélie Hallier and Thomas Bardainne, *Geophysics*, Vol. 89, Issue 1, KS13-KS23, January 2024.
Citation at https://pubs.geoscienceworld.org/seg/geophysics/article-abstract/89/1/KS13/630674/Rockfall-alarm-system-for-railway-monitoring?redirectedFrom=fulltext
From the abstract: We develop a seismic processing workflow for rockfall early warning, powered by dense arrays deployed along the track. The method is evaluated by dropping rocks from a controlled height and triggering rockfalls on a cliff. We indicate that seismic arrays are highly sensitive to small impacts and are able to detect them, locate them, and estimate their magnitude. The detection can be performed in near real-time with a simple algorithm because small-scale rockfalls produce impulsive waveforms near the impact. Precise localization with matched field processing is able to track the trajectory of a rockfall. Impacts against the steel rails may be recognized by their source signature. The seismic amplitudes are related to the rockfall volume by the Hertz law, which may be used to estimate their volume. These results indicate the potential of seismic-driven near real-time rockfall alarm systems.

"Towards Seismic-Powered Rockfall Alarm Systems for Railway Monitoring," Théo Rebert, Caifang Cai, Amélie Hallier and Thomas Bardainne, *29th European Meeting of Environmental and Engineering Geophysics*, Vol. 2023, pages 1-5, September 2023.
Citation at https://www.earthdoc.org/content/papers/10.3997/2214-4609.202320079
From the abstract: Railways are highly sensitive to rockfalls, and alarm systems exist to stop traffic when they occur. Existing alarm systems are mechanical triggers that suffer from frequent false alarms related to animal activity or vegetation growth. We introduce an alarm system powered by continuous recording on dense seismic arrays. To maximize the rockfall detection rate, the lines of accelerometers are deployed along the track, directly below the monitored cliff. The continuous data stream can be processed in near real-time for alarm detection thanks to a fast algorithm for impulsive events detection. At this scale, rockfalls are found to be strong impulsive sources of Rayleigh waves, which can be located automatically using [m]atched [f]ield [p]rocessing methods. As rockfalls emit strong signals with distinctive trajectories, seismic processing should be able to reliably identify them, even for small blocks (≈0.01 m^3), which are big enough to cause train derailment. The rockfall magnitude can be estimated from the signal energy. Experimental results suggest that impacts on the rail can be identified as they display a specific signature. This study paves the way towards rockfall alarm systems for railway monitoring powered by real-time automated seismic processing.

"Detecting Landslides and Rockfalls — Preventing Railway Accidents," Sensonic, *Railway News*, May 15, 2023.
https://railway-news.com/detecting-landslides-and-rockfalls-preventing-railway-accidents/
This article briefly describes a Sensonic landslide and rockfall alerting system, which "is based on fiber optic [d]istributed [a]coustic [s]ensing (DAS), an innovative technology that can detect landslides over long lengths of track via their vibration signature. A single sensor from Sensonic can listen to and detect landslides and rockfall along 80 km of route." The article presents five advantages for using optical fibers to sense ground movement vibrations over traditional methods of landslide and rockfall detection. *From the article*:

- It detects everywhere along the route. You do not need to find your problem sites — you can protect the entire route.
- It provides near real-time alerts of detected events together with exact location information. This allows action to be taken to prevent a natural hazard turning into a railway accident.

- Using optical [fibers] for vibration detection means no additional power sources are needed along the 80 km of [fiber-]powered from each Sensonic sensing unit. This makes it ideal for use in remote areas where power may not be readily available.
- The system does not require reset or re-arming after an alert.
- Optical fibers are robust and require no routine maintenance. If cable damage occurs, its location is accurately reported.

"Rock Falls Impacting Railway Tracks: Detection Analysis Through an Artificial Intelligence Camera Prototype," Andrea Fantini, Matteo Fiorucci and Salvatore Martino, *Wireless Communications in Transportation Systems*, Vol. 2017, Issue 1, January 2017.
https://onlinelibrary.wiley.com/doi/epdf/10.1155/2017/9386928
From the abstract:

> During the last few years, several approaches have been proposed to improve early warning systems for managing geological risk due to landslides, where important infrastructures (such as railways, highways, pipelines, and aqueducts) are exposed elements. In this regard, an Artificial intelligence Camera Prototype (AiCP) for real-time monitoring has been integrated in a multisensor monitoring system devoted to rock fall detection. An abandoned limestone quarry was chosen at Acuto (central Italy) as test-site for verifying the reliability of the integrated monitoring system. A portion of jointed rock mass, with dimensions suitable for optical monitoring, was instrumented by extensometers. One meter of railway track was used as a target for fallen blocks and a weather station was installed nearby. Main goals of the test were (i) evaluating the reliability of the AiCP and (ii) detecting rock blocks that reach the railway track by the AiCP. At this aim, several experiments were carried out by throwing rock blocks over the railway track. During these experiments, the AiCP detected the blocks and automatically transmitted an alarm signal.

Study results indicated the following:

- Suitability of the AiCP device in the site-test conditions for detecting obstacles over a railway track-target.
- Flexibility of the operating pixel threshold, which was calibrated based on the rock block size, for performing change detection analysis.
- Reliability of the detection algorithm for detecting rock blocks down to 20 cm.
- Reliability of the network transceiver installed on the main board of the AiCP for transmitting alarm signals, resulting from on-board change detection analysis.
- Suitability of the LED spotlight that allowed the AiCP device to operate in continuous mode, at night and in adverse weather.
- Efficiency of the power supply unit through periodic voltage check.

<u>North America</u>

"Rockfall Detection Using LiDAR and Deep Learning," Ioannis Farmakis, Paul-Mark DiFrancesco, D. Jean Hutchinson and Nicholas Vlachopoulos, *Engineering Geology*, Vol. 309, November 2022.
https://www.sciencedirect.com/science/article/pii/S0013795222003210
From the abstract:

> This paper investigates the potential of integrating sophisticated deep learning architectures into dynamic rockfall database population processes, with the goal of relieving experts from the daunting task of manually classifying rockfall events within large loads of change detection data.

> Deep neural networks based on the pioneering PointNet and PointNet++ architectures for 3D point cloud learning are developed for this purpose based on a [five]-year change detection database consisting of [more than] 8,000 rock slope clusters of identified change for training, with scanning intervals ranging from [five] days to [six] months. The models are tested on the 536 clusters from the two last data acquisitions to simulate the real monitoring situation and subsequently on the most frequent of the campaigns to increase the probability of working with single-event clusters. The best-performing model achieves an accuracy of about 89% and 84% on the last and shortest campaign, respectively. The optimized deep learning models are further evaluated on a geologically different rockfall database achieving almost 93% accuracy in a location where discrete geomorphologic features such as steep rock outcrops and erosion channels are present. The study shows that although it is challenging to achieve generalization in rockfall detection, site-specific training of the proposed deep learning architecture can lead to high-level performance and support further advancements in rockfall risk management.

The authors conclude that the "outcome of this research is promising regarding the potential for AI to be applied to attempt to prevent property and life loss from rockfalls in the future. Rockfall detection comprises the cornerstone for the development of an AI-based early-warning system, and [lidar] and [deep learning] can be the building blocks."

Contacts

CTC engaged with the individuals below to gather information for this investigation.

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Appendix A: Survey Questions

The online survey represented below was distributed via email to the member list of the TRB Geology and Geotechnical Engineering Section, the AASHTO Committee on Transportation System Operations and other selected contacts.

Caltrans Survey on Slide Detection, Monitoring and Alerting

The California Department of Transportation (Caltrans) is gathering information about the use of early detection, monitoring and alerting best management practices and technology for earth movement such as landslides, rockfalls and other natural hazards that occur in remote areas where telecommunications is absent. The agency's focus is more on practices related to ongoing, often slow-moving slides and less on debris flow or wildfire-related slides.

The survey below inquires about your agency's use of early warning systems for slide detection, monitoring and alerting. We estimate the survey will take approximately 20 minutes to complete. We would appreciate receiving your responses by [*approximately 2.5 weeks after the panel approves this project outline].*

If someone else in your agency would be more appropriate to address questions related to this issue, please forward this survey to that person.

The final report for this project, which will include a summary of the responses received from all survey participants, will be available on the Caltrans website.

If you have questions about completing the survey, please contact Carol Rolland at carol.rolland@ctcandassociates.com. If you have questions about Caltrans' interest in this issue, please contact Tori Kanzler at tori.kanzler@dot.ca.gov.

Thanks very much for your participation.

(Required) Please provide your contact information.

Name:
Agency:
Division/Title:
Email Address:
Phone Number:

Note: Responses to the question below determined how respondents are directed through the survey.

(Required) Does your agency use detection, monitoring and alerting best management practices and technology for landslides, rockfalls and other natural hazards occurring in rural, remote areas?

- No (Skipped the respondent to **Wrap-Up**.)
- Yes (Skipped the respondent to **Early Warning Systems and Practices**.)

Early Warning Systems and Practices

1. What types of detection and monitoring methods does your agency use to detect and monitor land movement? Please select all that apply.
    - Distributed acoustic sensing
    - Lidar
    - Network of weather stations and radio systems
    - Remote sensing techniques (e.g., satellite radar images)
    - Scanning radar systems
    - Surveying and sensing instrumentation
    - Video cameras
    - Other (Please describe.)
2. Please describe the key features of the practice or system, including the name of the product(s), vendor(s) and cost (initial and ongoing operations and maintenance).
    Product(s):
    Vendor(s):
    Initial cost:
    Ongoing cost:
3. What factors are monitored to assess slide behavior and forecast a potential slide? Please select all that apply.
    - Environmental variables
    - Ground vibrations
    - Pore water pressure development
    - Seepage patterns
    - Terrain characteristics
    - Water content
    - Other (Please describe.)
4. How is data collected and transmitted?
5. Which organizations/entities receive the alerts? Please select all that apply.
    - Traffic management center
    - Maintenance operations
    - Other (Please describe.)
6. How are alerts delivered? Please select all that apply.
    - Email
    - Phone
    - SMS alert (Short Message Service text messaging service; up to 160 characters per text.)
    - Other (Please describe.)
7. How is the traveling public notified of a hazard incident or road closure? Please select all that apply.
    - Actuate a flashing beacon
    - Generate audio-visual alarm
    - Post notice to dynamic message sign
    - Post notice to 511 real-time traveler information service
    - Other (Please describe.)
8. If the public is notified of a closure due to a slide, is the notification an automated process or does it require manual intervention from a human operator such as a traffic management center operator, maintenance staff member or other staff member?
9. Please briefly describe the operating process of your agency's system, from detecting movement to sending an alert.

10. Please briefly describe how your agency uses these systems in the other applications listed below.
    Debris flow:
    Mudslides:
    Wildfire burn scar areas:
    Other applications:

Assessment

1. What are the benefits of using this system/practice?
2. What challenges has your agency experienced with this system/practice?
3. Please provide links to documents associated with your agency's use of slide detection, monitoring and alerting best management practices and technology. Send any files not available online to carol.rolland@ctcandassociates.com.

Wrap-Up

Please use this space to provide any comments or additional information about your previous responses.