# Final Report: Sustainable Geotechnical Asset Management along the Transportation Infrastructure Environment Using Remote Sensing

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**Michigan Technological University**

USDOT Cooperative Agreement No. **RITARS-14-H-MTU**

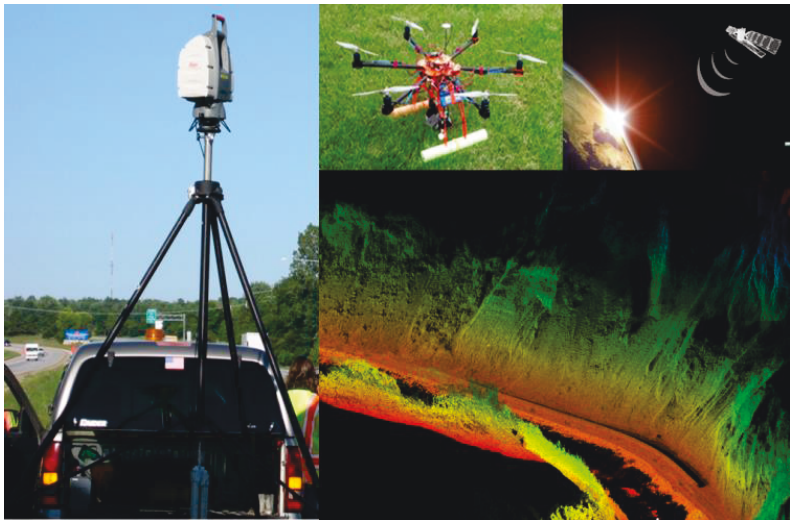

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TABLE OF CONTENTS

GLOSSARY OF TERMS

| | |
|---|---|
| AASHTO | American Association of State Highway and Transportation |
| ADTT | Average Daily Truck Traffic |
| AEG | Association environmental and engineering geologists |
| ALOS | Advanced Land Observing Satellite |
| ASI | Italian Space Agency |
| Austroads | Australian road transport and traffic agencies association |
| BAM | Bridge asset management |
| BMS | Bridge Management System |
| CCD | Charge-Coupled Devices |
| CD | Compact disk |
| CinOptic | Michigan Tech University student media enterprise |
| COSMO-SkyMed | COnstellation of small Satellites for the Mediterranean basin Observation |
| CSA | Canadian Space Agency |
| DAMA | Data Management Association |
| DEM | Digital Elevation Model |
| DLR | German Aerospace Center |
| DOT | Department of Transportation |
| DSI | Distributed Scatterer Interferometry |
| DSLR | Digital single lens reflex |
| DSS | Decision Support System |
| EAM | Embankment asset management |
| ENVISAT | Environmental Satellite from the European Space Agency |
| ERS | Environmental Research Satellite |
| ESA | European Space Agency |
| FHWA | Federal Highway Administration |
| GAM | Geotechnical asset management |
| GAMDSS | Geotechnical asset management decision support system |
| GIS | Geographic Information System |
| GNSS | Global Navigation Satellite Systems |

| | |
|---|---|
| GPS | Global positioning system |
| GUI | Graphical User Interface |
| H/L | Height to length ratio |
| HTML | Hypertext Markup Language |
| INS | Inertial navigation system |
| InSAR | Interferometric Synthetic Aperture Radar |
| ISTEA | Intermodal Surface Transportation Act |
| JAXA | Japanese Aerospace Exploration Agency |
| JERS | Japanese Earth Resource Satellite |
| KML | Keyhole Markup Language |
| LiDAR | Light Detection and Ranging |
| LTBP | Long-Term Bridge Performance |
| MDOT | Michigan Department of Transportation |
| MRP | Maintenance Rating Program |
| NBIS | National Bridge Inventory System |
| NCHRP | National Cooperative Highway Research Program |
| NED | National Elevation Dataset |
| OGC | Office of Government Commerce |
| PALSAR | Phased Array type L-band Synthetic Aperture Radar |
| PAM | Pavement asset management |
| PBLC | Portuguese Bend Landslide Complex |
| PMS | Pavement Management System |
| PostgreSQL | Object-relational database management system |
| PSI | Persistent Scatterer Interferometry |
| RADARSAT | Canadian Space Agency Earth Observation Satellite |
| SAM | Slope asset management |
| SAR | Synthetic aperture radar |
| SLC | Single look complex |
| SNR | Signal to noise ratio |
| SqueeSAR™ | InSAR processing algorithm by TRE |
| TAC | Technical Advisory Committee |

| | |
|---|---|
| TAM | Transportation asset management |
| TerraSAR-X | Radar Earth Observation Satellite from the German Aerospace Center |
| TRB | Transportation Research Board |
| TRE | Tele-Rilevamento Europa |
| USDOT | Unites States Department of Transportation |
| USM | Unstable Slope Management |
| UAV | Unmanned Aerial Vehicle |
| USGS | Unites States Geologic Survey |
| WMS | Web Mapping Services |

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**Executive summary**

This report summarizes the work and results obtained from USDOT Cooperative Agreement No. RITARS-14-H-MTU, on remote sensing applications for geotechnical asset management. Considering the context of transportation asset management, a framework for the application or remote sensing tools is developed, particularly for monitoring geotechnical asset surface displacement, as part of the monitoring necessary for geotechnical asset management. A review of the transportation asset management paradigm is given in chapter 1, and the requirements for remote sensing based geotechnical asset management are explored in chapter 2. A survey on current practices, perceived needs and limitations gives an overview of the perspective of transportation agencies on this topic. Appropriate technologies are identified and selected for the tasks most relevant to geotechnical asset management, as explained in chapter 3. Field verification and evaluation of the remote sensing technologies is reported in chapter 4, always within the context of geotechnical asset monitoring.

The monitoring of geotechnical assets has the goal of continuously or frequently assess the assets' performance, according to the transportation management needs. Chapter 5 discusses asset performance definition and monitoring. Using the geotechnical asset condition information obtained from the monitoring requires some framework for decision making, the decision support system discussed in chapter 6 presents a web framework that contribute to this goal. Any implementation of new technology or methods requires and evaluation of its benefits, weighted against the costs of adopting such technologies, chapter 7 explores the costs of implementing remote sensing methods, and the value of the information that can be obtained from them.

For transportation agencies to adopt the new technologies and implementation framework is necessary. Chapter 8 discusses the implementation framework for the remote sensing technologies tested in the project, giving also hypothetical examples on two of the field sites included in the project. The outreach components of the project are summarized in chapter 9, including the development of an outreach video and the multiple conference presentations and papers that were generated during the duration of the project.

## Chapter 1: Background

### 1.1 Asset Management

The term *asset management* is defined differently by each individual, government agency, or corporation, yet essentially means the same thing. In general, any actions implemented to maintain, preserve, or to perpetuate an asset's optimal performance level throughout its lifespan fall under the asset management umbrella. Transportation agencies each have their own official term. In a report entitled *Strategy for improving asset management practices*, the Australian road transport and traffic agencies association (Austroads) defined asset management as "…a comprehensive and structured approach to the long-term management of assets as tools for the efficient and effective delivery of community benefits." (Austroads, 1997). The Federal Highway Administration (FHWA) expanded on this definition two years later:

> "[Asset management is] a systematic approach of maintaining, upgrading, and operating physical assets cost effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision making [sic]. Thus, asset management provides a framework for handling both short- and long-range planning." (p8, FHWA, 1999)

Iterations of the asset management definition have been produced since and include portions of the FHWA definition. For example, the Michigan Department of Transportation (MDOT) defines asset management as "…a process to strategically manage our transportation system in a cost-effective and efficient manner" (MDOT, 2015); Flintsch & Bryant, Jr. (2006) define it as "…a strategic approach to the optimal allocation of resources for the management, operation, maintenance, and preservation of transportation infrastructure"; the National Cooperative Highway Research Program (NCHRP) describe a portion of it as "…a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their life cycle…" (Cambridge Systematics, Inc., et al., 2009). Regardless of the myriad of definitions and repetitive verbiage, everyone seems to agree that basic asset management requires the maintenance, management, and preservation of all assets along the transportation corridor.

Although many goals of asset management are included in the definition, the American Association of State Highway and Transportation (AASHTO) summarized the goals into three general statements (Cambridge Systematics, Inc. et al., 2002). The first goal is to "build, preserve, and operate facilities" in a manner that is more "cost-effective" and with an improvement in "asset performance." The second goal is to the consumers the "best value for the public tax dollar spent." The third goal, which is more political, is to "enhance the credibility and accountability of the transportation agency to its governing executive and legislative bodies." Of these three goals, methodologies towards accomplishing the first two goals have been studied in great detail, as the third goal is a by-product of the first two.

The United States (US) was relatively late to the asset management game. Asset management programs were implemented in other countries (Canada, Australia, New Zealand, and across Europe) in the 1980s and 1990s. The first US-based seminar was held in the Washington, D.C., in 1996 with AASHTO and FHWA as hosts. The overwhelming positivity felt from this seminar lead to successive annual meetings, beginning in 1998 with the Asset Management National Conference in Scottsdale, Arizona. Then in 2000, the Transportation Research Board (TRB) joined AASHTO and FHWA to create an "AM [Asset Management] Task Force" (Hawkins & Smadi, 2013). Since then an increase in research and funding has gone toward many forms of asset management (e.g., pavement, transportation, bridge, geotechnical, tunnel, etc.) with the US Department of Transportation (USDOT) and many state DOTs including some sort of asset management protocol in their annual infrastructure budget. Then on July 6, 2012, law P.L. 112-141 – the Moving Ahead for Progress in the 21st Century Act (MAP-21) was signed into law (USDOT, 2015). MAP-21 requires the development of "a risk-based asset management plan for the National Highway System to improve and preserve the condition of the assets and the performance of the system" (p1660, Stanley & Pierson, 2013). Transportation asset management (TAM) is the most widespread asset management plan, with at least 16 states have some sort of TAM plan currently in place (e.g., Colorado, Connecticut, Florida, Georgia, Indiana, Michigan, Minnesota, Missouri, Montana, New Jersey, North Carolina, Oregon, Pennsylvania, Utah, Virginia, and Washington – Lindquist & Wendt, 2012). All of these TAM plans include some, but not all, of other various asset types (e.g., pavement, bridges, geotechnical, tunnels), as other asset types usually are separated into other management plans. For example, DOTs in Washington, Oregon, California, and many other western states

have a separate rock fall/landslide hazard program. So basically for those state DOTs with no existing asset management plan, the most difficult part is how to start; while for those states with existing TAM plans, the biggest problem is integrating all asset management plans into one system or network.

### 1.2 Current Practices in Asset Management

Current practices in asset management vary greatly by transportation agency and again by asset type. The initial asset management approach was to divide focus by asset type and then create individual asset management programs. This resulted in the generation of TAM, pavement asset management (PAM), bridge asset management (BAM), geotechnical asset management (GAM), slope asset management (SAM), embankment asset management (EAM), and so on and so forth. The obvious problem with this divide-and-conquer approach is that separate management plans do not share data or information with any other plan. This can pose a problem since a variety of assets share the same transportation corridor. For example, one slope failure could potentially affect assets categorized in all of the management programs listed above. Even worse, some types of asset management systems do not have standard procedure between states DOTs or transportation agencies; Vessely (2013) laments that "…there does not appear to be a standard of practice for geotechnical asset management [GAM] within state and federal transportation agencies in the United States" (p35). Therefore the need for an integrated asset management approach is apparent and, according to Anderson & Rivers (2013), recent recommendations have been made to change the focus from an "asset-by-asset approach to one that examines the entire corridor."

Differences by transportation agency and asset type notwithstanding, many DOTs and agencies have adopted a common asset management approach, which has been dubbed the *worst-first approach*. The approach is quite simple: assets that have failed or have degraded to the point of disrepair are either repaired or entirely replaced (FHWA, 1999). There may be two reasons why a worst-first approach is more common than a preventative approach: (1) tight budgets and limited funding require addressing the most critical assets, a reactive approach due to safety concerns, as opposed to spending the money on proactive measures; (2) justification to the consumers for a proactive and preventative approach is difficult because the tax-payers

essentially expect the assets in the worst condition are addressed first and that, essentially, preservation is interpreted as "fixing something that isn't broken" (p21, FHWA, 1999).

In lieu of these reasons, the worst-first approach has been deemed unsustainable. The FHWA admit that "most states limit application of their management systems to monitoring conditions and then plan and program their projects on a worst-first basis" and that this approach is "tactical rather than strategic" (p16, FHWA, 1999). Stanley & Pierson (2013) go one step further and claim the worst-first approach "results in overall system degradation as no assets receive preventative maintenance in time to keep the investment optimized" (p1660). So although a short-term fix of one failed asset may be cheaper, may receive more publicity, and is much easier to explain to the general public ("It was fixed because it failed!"), it is actually much more dangerous and, on a longer timeframe, the worst-first approach is more time-consuming and costly than a preventative approach.

This understanding has led to the creation of many asset management procedures and workflows. The following sections describe two general asset management workflows (FHWA and AASHTO) and a risk-based approach framework (Mian et al., 2011) along with a handful of specific management systems, including: the Bridge Management System, the Long-Term Bridge Performance Program (FHWA), the Maintenance Rating Program, the Pavement Management Guide (AASHTO, 2001), a few statewide DOT-based Unstable Slope Management Programs, and an Asset Management of Embankments program used in the United Kingdom (Glendinning et al., 2009).

### 1.3 FHWA Generic Asset Management Framework (FHWA, 1999)

The FHWA created a generic asset management framework (Figure 1.1) to illustrate that all asset management plans should focus on strategy, a preventative approach, as opposed to tactics, a reactive approach. This flowchart aims to provide the foundation for an asset management procedure and can be applied on any scale: asset-by-asset, transportation corridor, or entire network.

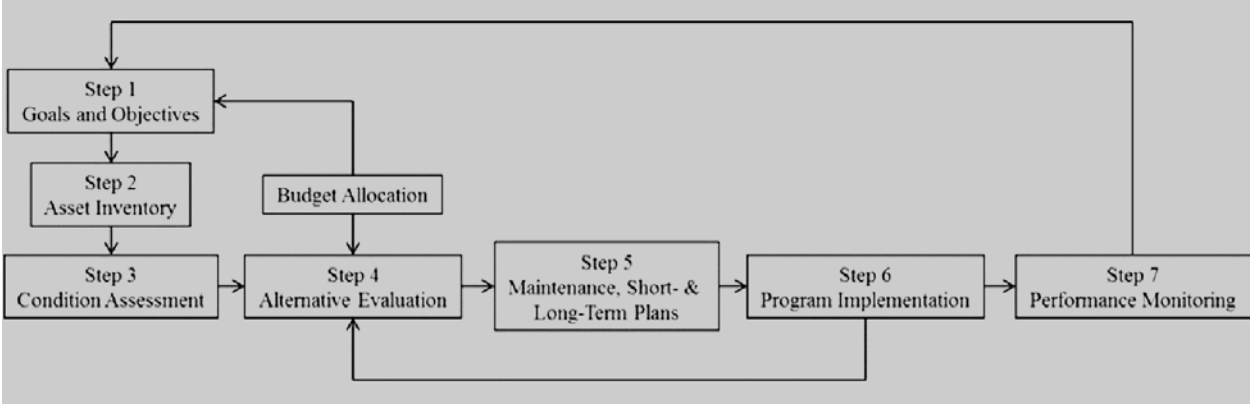


***Figure 1.1:*** *The seven steps, along with budget allocation, that comprise the generic asset management framework created by the FHWA (recreated from FHWA, 1999).*

**Step 1: Goals and Objectives.** Goals and objectives, which may take the form of policies and laws, must first be addressed prior to any actions taken. These goals should align with realistic expectations for what the asset management program can accomplish. Factors such as available budget, resources, workforce, and logistics should be examined as potential limitations and taken into account. The result of Step 1 should include a full understanding of management goals and objectives, which should in some way reflect the constituents' needs, and intended targets should be set for the rest of the generic asset management framework.

**Step 2: Asset Inventory.** The construction of the asset inventory is a difficult and time-consuming step. Important questions must be answered before beginning the inventory, such as: (1) which assets should be included in, and excluded from, the inventory? (2) What information should be recorded for each asset (e.g., location, value, functions, services, condition, etc.)? (3) How will the asset information be recorded (e.g., spreadsheet, GIS geodatabase, etc.)? (4) How will field crews be trained to record subjective information in a consistent manner? The scope of constructing an asset inventory can be daunting, especially when considering scales of entire transportation networks on the state or federal level. Although initially time-consuming, the creation of an asset inventory would only need to be completed once and then updated as new assets are constructed or destroyed and existing assets receive maintenance or upgrades.

**Step 3: Condition Assessment.** This step aims to identify the condition of each asset and apply forward modeling to predict asset condition change over time. An initial condition assessment may have been included in the asset inventory (Step 2). The type of assessment would vary drastically by asset type – it would not make sense to have the same criteria for

tunnels as for bridges. The current asset condition as well as historical asset condition and performance assessments are recommended for adequate performance modeling. The goal of this step is to utilize "analytical tools and reproducible procedures [to] produce viable cost-effective strategies for allocating budgets to satisfy agency needs and user requirements, using performance expectations as critical inputs" (p18, FHWA, 1999).

**Step 4: Alternative Evaluation.** Alternate choices and budget allocations are then reevaluated if necessary. Any ways to optimize the asset management program should also be considered. This step is a quality control measure.

**Step 5: Maintenance with Short- and Long-Term Plans.** Building on what was accomplished through Steps 2-4, short- and long-term maintenance plans are prepared based on the information gained. Short-term plans would include reactive measures such as repairing critically deteriorated assets, replacing assets that have failed, and addressing threats to public safety or substantial damage to assets in the transportation environment. Long-term plans would incorporate preventative measures through the use of asset condition assessment criteria (e.g., risk-based or hazard-based) that identify assets in need of care via life-cycle monitoring.

**Step 6: Program Implementation.** This step is pretty basic – the asset management program now begins. The importance of this step is that, depending on the asset management program performance, it can either lead back to Step 4, if the program requires additional optimization, or lead forward to Step 7.

**Step 7: Performance Monitoring.** The final step of the generic asset management framework is to assess the performance of the framework which, according to the FHWA, should be conducted annually. The framework becomes more flexible and dynamic with a repetitive self-evaluation mindset because external changes, such as varying budget and funding amounts, can be addressed in a timely fashion – or as stated by the FHWA: "…any Asset Management system should be flexible enough to respond to changes in any of these variables or factors [policies, goals, asset types and characteristics, budgets, State operating procedures, and business practices]" (p18, FHWA, 1999).

### 1.4 AASHTO Asset Management Plan (AASHTO, 2013)

AASHTO has also provided a list of eight components an asset management plan should include:

1. Data Management. As defined by the Data Management Association (DAMA), data management is "…the development, execution and supervision of plans, policies, programs and practices that control, protect, deliver and enhance the value of data and information assets" (p4, DAMA, 2009). Management of data within an asset management plan would include the organization of data obtained from various technologies (e.g., hand-written field notes or data collected from the field in differing formats, asset pictures, computer spreadsheets, GPS data, etc.) as well as big data storage, access, and visualization (Vessely, 2013), which may include compiling all data into a geodatabase.
2. Inventory and Condition Surveys. This component is identical to Steps 2 and 3 of the generic asset management framework (FHWA, 1999). AASHTO (2013) does provide a list of specific information that should be provided for each asset:
    a. Performance Measures
        i. Current asset performance rating
        ii. Current asset performance with respect to the entire network
        iii. Trend analysis (historic asset performance)
        iv. Predictive analysis (potential future performance)
    b. Geographic Location
    c. Jurisdiction Data
    d. Functional and Utilization Data
    e. Performance Characteristics
    f. Construction History and Historical Significance
    g. Archive of Valuable Documents
3. Levels of Service: which are defined as "…classifications or standards that describe the quality of service offered to road users, usually by specific facilities or services against which service performance can be measured" (p21, AASHTO, 2013). Levels of service are then divided into two groups: (1) customer, how the public interacts with the service, and (2) technical, what is required by the transportation agency or service provider.
4. Service Life. This is an understanding of how an asset's performance changes from deterioration over time. Service life is usually shown in plot-format, with a performance metric decreasing over time and a comparison between asset preservation and total asset deterioration (e.g., Figure 1.2).

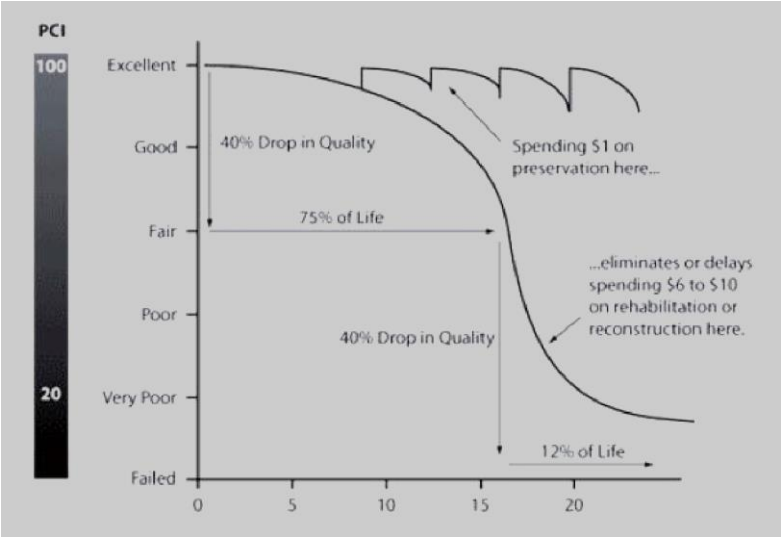


***Figure 1.2:*** *Hypothetical pavement deterioration curve plotting time the pavement condition index (PCI – y-axis) over time (x-axis). The saw-tooth curve displays the benefits of a preservation approach compared to the more common worst-first approach, which may lead to significant deterioration (main curve). Plot was taken from Galehouse et al. (2006).*

5. Performance Measures (Outcome Measures) and Condition Indices. Performances measures quantify the successfulness of the asset management plan; these variables can also be used as a form of performance quality control. AASHTO's transportation asset management plan includes eight performance measure areas: (1) condition, (2) life-cycle cost, (3) safety, (4) mobility, (5) reliability, (6) customer measures, (7) externalities, and (8) risk (p16, AASHTO, 2013). Seven performance measures included as goals in MAP-21 are: (1) safety, (2) infrastructure condition, (3) congestion reduction, (4) system reliability, (5) freight movement and economic vitality, (6) environmental sustainability, and (7) reduced project delivery delays (USDOT, 2013).
6. Risk Management. Risk is defined as any threat to transportation infrastructure and operations regardless of cause (AASHTO, 2013). Therefore, risk management is the practice of identifying, analyzing, and mitigating sources of risk. The generation of a risk-based approach framework (e.g., see next section – Mian et al., 2011) where the frequency, likelihood, and/or probability of a risk occurrence is estimated, is the general goal.

7. Life Cycle and Cost-Benefit Analyses. A life cycle analysis examines the change in asset performance, cost, deterioration, and potential risk over an asset's lifespan. A cost-benefit analysis is a method of calculating the financial pros (benefits) and cons (costs) of a particular activity or function. In terms of asset management, benefits may include the savings acquired due to an asset's performance or the projected savings of asset preservation instead of total asset failure, while costs may include the actual expense of asset preservation. The value of an asset is determined by the cost of the asset subtracted from the benefit of the asset; an asset has positive value if the benefits are greater than the costs.
8. Decision Support System (DSS). A DSS addresses the following: (1) the needs of an asset management plan and potential solutions, (2) evaluation of options, and (3) an analysis of asset performance with respect to investment (AASHTO, 2013).

### 1.5 Risk-based Approach Framework

The framework for the risk-based approach presented by Mian et al. (2011) could be incorporated into the Condition Assessment (step 3) and/or Alternative Evaluation (step 4) of the FHWA generic asset management framework (FHWA, 1999) or the Risk Management step of the AASHTO Asset Management Plan (AASHTO, 2013). For the purposes of this framework, the definition of 'risk' provided by the Office of Government Commerce (OGC) of the United Kingdom is used, which states:

> "Risk is an uncertain event or set of events that, should it occur, will have an effect on the achievement of objectives. A risk is measured by a combination of the probability and the magnitude of its impact on objectives." (OGC, 2007)

The framework consists of five steps (labeled Step 0-4 by Mian et al., 2011) which work to combine asset management with risk management.

- Step 0: Decision Scope – the scope is clearly defined and should include the following information: (1) identification of "service aspect and level" (p2, Mian et al., 2011), (2) duration of time the framework will be implemented, and (3) geographic location(s) of assets, transportation corridor, and/or network.

A determination between a proactive approach and a reactive approach must be decided upon as well. A proactive approach is one where incremental maintenance reduces the probability of unexpected repairs; a reactive approach, which may be less expensive on the short-term (and funding can be easier to justify to the public), increases the probability of incidental repairs and may conflict with performance measures (e.g., life-cycle cost, mobility, and safety - AASHTO, 2013; almost all listed in the MAP-21 guidelines – USDOT, 2013). Basically all asset management plans strive for a proactive approach.

- Step 1: Hazard Identification – a hazard is any "uncertain event or set of events" that lead to risk within the transportation environment. Hazards must be identified by type, magnitude, cause, and impact on service, goals, objectives, and performance measures.
- Step 2: Risk Estimation – the calculation of the "likelihood" and "consequence" of the risk event occurring, which yields a quantifiable output (Mien et al., 2011). Likelihood is defined as the probability that an event, that has already occurred, would result in a defined outcome. The consequence is the resultant negative impact, or severity (in magnitude), from a certain risk. Therefore $R=L \cdot C$ defines the relationship between risk (R), likelihood (L), and consequence (C) over a period of time (Woodruff, 2005). An output could be in the form of a risk matrix (Figure 1.3). A risk matrix compares the likelihood (rows) and consequence/impact (columns) to calculate the risk event level. Risk matrices can be either qualitative or quantitative, with the latter being the preferred choice but also requires more data.

| Likelihood | Impact | | | | |
|---|---|---|---|---|---|
| | Insignificant | Minor | Moderate | Major | Severe |
| Almost certain | Moderate | High | High | Extreme | Extreme |
| Likely | Moderate | Moderate | High | High | Extreme |
| Possible | Low | Moderate | Moderate | High | Extreme |
| Unlikely | Low | Moderate | Moderate | Moderate | High |
| Rare | Low | Low | Moderate | Moderate | High |

***Figure 1.3:*** *Example of a qualitative risk matrix (Lee Merkhofer Consulting, 2014).*

- Step 3: Risk Evaluation – a two-fold step that defines the maximum risk threshold and mitigation. The maximum risk threshold is the greatest risk allowable for an asset to be considered 'safe' or not require mitigation. For example, if the maximum risk threshold were set to 'Low' in the risk matrix in Figure 1.3, then all assets with a 'Moderate,' 'High,' or 'Extreme' risk would require mitigation actions to be performed. According to Mien et al. (2011), mitigation may take three forms: "… (1) essential intervention for *critical* risks, (2) intervention desirable but not essential, for *moderate risks* or (3) no intervention necessary for *low* risks. The middle category associated with *'moderate risks'* is the one that requires the most detailed evaluation and where 'risk tolerance' [or maximum risk threshold] becomes an essential part of the decision making" (p4, italics in original text).
- Step 4: Risk-based Decision Making – finally a decision should be made on what kind of mitigating action (if any) is required based on many factors, including the risk level, the assets at risk, the impact on performance measures, etc. The goal of this framework is to determine an acceptable risk tolerance at a given scale (asset, corridor, and network) and identify those assets that require further action. Since event risk changes through time, this framework should be repeated at an interval deemed sufficient for proper asset and risk management.

### 1.6 Maintenance Rating Program

The Maintenance Rating Program (MRP), developed in 1985 by the Florida DOT (FDOT), is a highway asset condition assessment plan on the state level. At least once per year, State DOTs are tasked with assigning condition ratings to assets along state highway transportation corridors. Rated corridor elements include roadway, roadside, vegetation and aesthetics, traffic signs, and drainage systems (USDOT, 2007). The maximum rating for each category is 20 and, therefore, a perfect total rating of 100 is possible. An 80 was originally set as a passable grade by the FDOT, but since then other states have had the option to alter their target rating. For example, the North Carolina Turnpike Authority aims for an overall rating of 90/100 for the Triangle Expressway system (NCTA, 2014).

Workers must undergo state-run MRP computer-based training and pass the MRP Handbook Exam (FDOT, 2013). The goal is to develop a uniform asset rating style from State DOT employees so that all state's MRP ratings are consistent, while also dividing up the inventory rating work into smaller geographic regions.

Unfortunately, to date only six US states (Figure 1.4) and Taiwan (Chou et al., 2006) have (at least partially) adopted the MRP. Although the MRP may work well at the state-level, the immediate limitation is the lack of MRP acceptance among many states and, consequently, little consistency for how assets are rated.

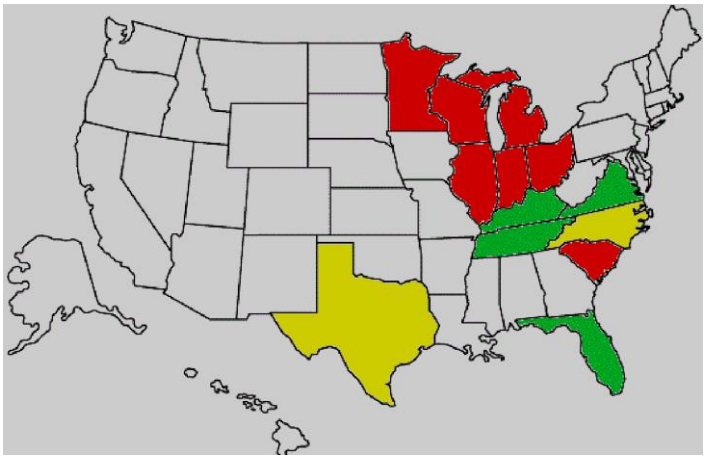

***Figure 1.4:*** *US states that have considered the MRP for highway asset condition assessment. Green-colored states run annual data collections across most, if not all, of their state highway systems. Yellow-colored states employ the MRP for geographically-limited use (not statewide). Red-colored states have published a report on the potential benefits of MRP or have expressed interest in developing an MRP system, but have not executed the program or have instead constructed a different plan.*

### 1.7 Oregon DOT-I: Rockfall Hazard Rating System

The Rockfall Hazard Rating System was created by the ODOT in the 1980s. This system contains six main features (Pierson, 1991):

1. A uniform method for slope inventory.
2. A preliminary rating of all slopes. Slopes were initially rated based on the estimated potential for rock on the roadway and historical rock fall activity. In both categories, the slope would receive an "A" rating if high, "B" rating if moderate, and "C" rating if low.

"A" rated slopes then proceed to the detailed rating, while "B" rated slopes will be addressed if time permits and "C" rated slopes discarded.

3. A detailed rating of all hazardous slopes. The detailed rating would assign a numerical value, from 1 to 100, to each slope based on the following criteria:
    a. Slope height – the vertical height of the slope from which a rock fall is expected
    b. Ditch effectiveness – the ability of roadside ditches to restrict falling rocks from reaching the roadway
    c. Average vehicle risk – the percentage of time that a vehicle will be present in the rock fall hazard zone
    d. Percent of decision sight distance – an estimation of the length of roadway, in feet, a driver must have to make a complex decision, based on vehicle speed, with respect to the actual length of roadway a driver would have to make the maneuver
    e. Roadway width – distance from edge of pavement on one side of the road to the edge of pavement on the opposite side
    f. Geologic character – attempts to describe slope characteristics based on geology
    g. Block size or quantity of rock fall per event – a representative estimation of size and amount of rock fall content per event
    h. Climate and presence of water on the slope
    i. Rockfall history – chosen from the following options: few falls, occasional falls, many falls, and constant falls.

A score is assigned to each of the variables listed above. The Rockfall Hazard Rating System uses only four score options – 3, 9, 27, 81, with greater values indicating more hazardous slopes – although Pierson claims "…[these score values] are representative scores of a continuum of points from 1 to 100" (p3, Pierson, 1991).

4. A preliminary design and cost estimate for more serious sections.
5. Project identification and development. Pierson (1991) identifies four ways the results from the Rockfall Hazard Rating System may be used to determine projects for construction.
    a. Slopes are chosen based on the rating score.
    b. Slopes are chosen based on the rating score relative to the construction cost.

c. Adjacent slopes that require similar mitigation procedures are grouped together and chosen based on areal extent.
d. Slopes are chosen based on the rating score and proximity to important transportation infrastructure.
e. Annual review and update.

Eight other USM plans were constructed based on the Rockfall Hazard Rating System of Pierson (1991) and ODOT: (1) ODOT-II, an updated version by the Oregon DOT, (2) OHDOT from the Ohio DOT, (3) NYSDOT from the New York State DOT, (4) UDOT from the Utah DOT, (5) WSDOT from the Washington State DOT, (6) TDOT from the Tennessee DOT, (7) MODOT from the Montana DOT, and (8) BCMoT from the British Columbia Ministry of Transportation (Huang et al. 2009).

### 1.8 Asset Management of Embankments – United Kingdom (Glendinning et al., 2009)

The embankment management framework described by Glendinning et al. (2009) and Perry et al. (2003) begin with a risk assessment flowchart (Figure 1.5) and includes a strategic level and a tactical level. The strategic level examines all the slopes in the transportation network and includes steps similar to the construction of an asset inventory, slope prioritization based on risk analysis, maintenance, and asset monitoring. The tactical level focuses on individual slopes and includes steps such as condition assessment, potential mitigating actions needed, risk analysis, cost-benefit analysis, and short- and long-term planning.

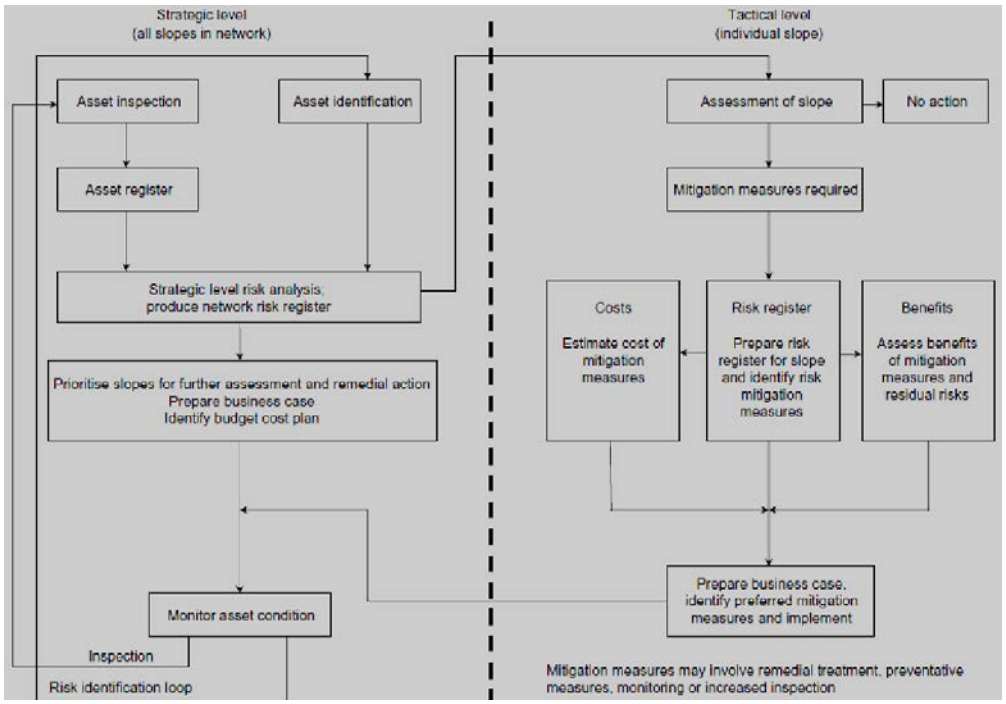


***Figure 1.5:*** *Embankment management framework at the strategic and tactical levels (Glendinning et al., 2009).*

Some specifications to the framework were given in Glendinning et al. (2009). Regular inspections of the assets are performed to assess the current condition of the asset and placed in an inventory (asset register). Risk analysis is performed by combining the current condition assessment information with "…historical information in some sort of database… [t]he history plus the current condition provides information on the possible potential for failure" (p111, Glendinning et al., 2009) and coupling that information with a risk matrix approach (Figure 1.3) where "…the consequences of failure including safety and commercial risks… [such as] volume of traffic, value of the route, diversionary route availability and its strategic importance to the movement of freight" (p111). Funding and resources are directed where they are most required and, therefore, maintenance, monitoring, and remediation are performed if and where necessary.

## 1.9 Limitations of Current Asset Management Plans

Many limitations exist with either (1) the current asset management plans, or (2) implementation shortcomings of current asset management plans by state or federal DOTs.

Below are listed eleven limitations, challenges, or areas within the asset management field that require more research concentration.

- **Limitation #1:** State-wide inventories are massive.
- **Limitation #2:** Incomplete inventories.
- **Limitation #3:** Different asset types require different methods for measuring condition.
- **Limitation #4:** Condition variation in time is difficult to predict.
- **Limitation #5:** There exists no good method for predicting large failures from observed deterioration.
- **Limitation #6:** Geotechnical asset management programs are minimal in scope.
- **Limitation #7:** Geotechnical asset life-cycle is poorly understood.
- **Limitation #8:** Future spending estimates are based on present asset deterioration models – actual spending varies greatly when assets do not deteriorate as projected (asset life-cycle is poorly understood).
- **Limitation #9:** The sundry of asset management programs implemented on many levels, by many agencies/organizations with individual performance measures, results in incompatible datasets.
- **Limitation #10:** Problems experienced by local governments.
- **Limitation #11:** Additional research is needed.

## Chapter 2: Requirements for Remote Sensing Based Geotechnical Asset Management Systems: Survey on current practices, Perceived Needs and Limitations, by transportation agencies.

The discussion on transportation asset management practices presented in this chapter is applicable to transportation assets in general. In this section we present results from an online survey we performed amongst transportation agencies, inquiring about current practices, perceived needs and limitations of geotechnical asset management.

### 2.1 Methodology

The goal of the survey was to get investigate the current practices, perceived needs and perceived limitations of geotechnical asset management amongst professionals and practitioners within transportation agencies. Potential survey respondents were chosen from public contact information records, mainly via internet pages of transportation agencies, and a few were contacted through project participant contacts. Email invitations to participate in the survey were sent to 710 individuals working in transportation agencies in all 50 states of the Union, and a few professionals working in private railroad companies. A two months period was allowed for potential participants to fill the survey, after this period 99 individuals had completed all questions in the survey, and an additional number of participants had partially answered some parts of the survey. The design, data collection and analysis of the survey followed Federal Regulations on the use of human subjects in survey studies, and was overseen and approved by the Michigan Technological University Institutional Review Board.

The survey was designed in an online platform (https://www.surveymonkey.com), for the respondents' convenience. The survey is divided in three sections, the first one contains questions about the respondent's background, including the agency they work for and their main job in that agency. The second section asks questions about the current practices involving geotechnical assets at the respondent's agency. The third section asks questions about the perceived needs and limitations regarding geotechnical asset managements at their respective agencies. The actual questions can be seen in the corresponding appendix section.

## 2.2 Results of the survey

Survey respondents came from a wide geographic distribution, Figure 2.1 shows a map of the number of respondents per state. This sample seems reasonably representative of transportation agencies nationwide, covering a variety of geographic locations, with different geotechnical challenges and institutional settings.

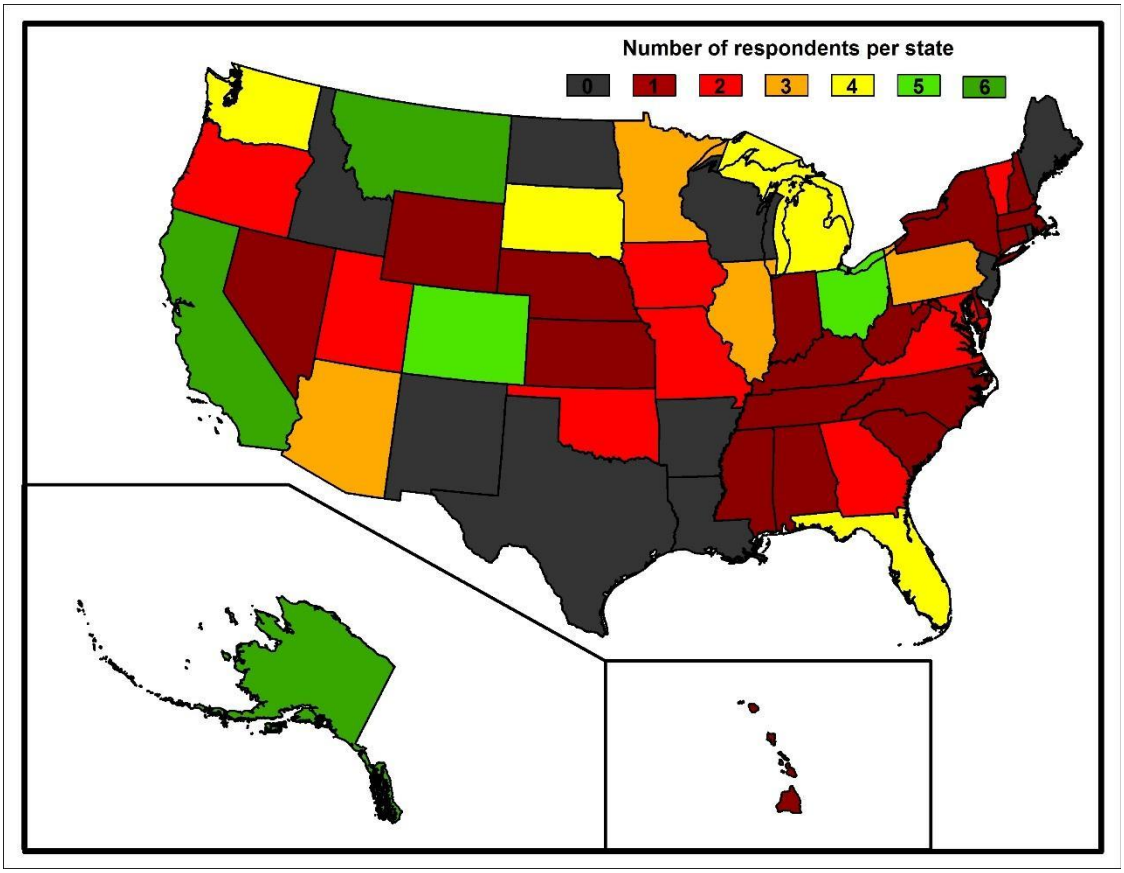


***Figure 2.1:*** *Survey respondents per state. A majority of the respondents (72.7%) reported having a geotechnical or geological background, as show in Figure 2.2. This is significant to interpret the rest of answers, as it suggests that they would be familiar with the importance of geotechnical assets.*

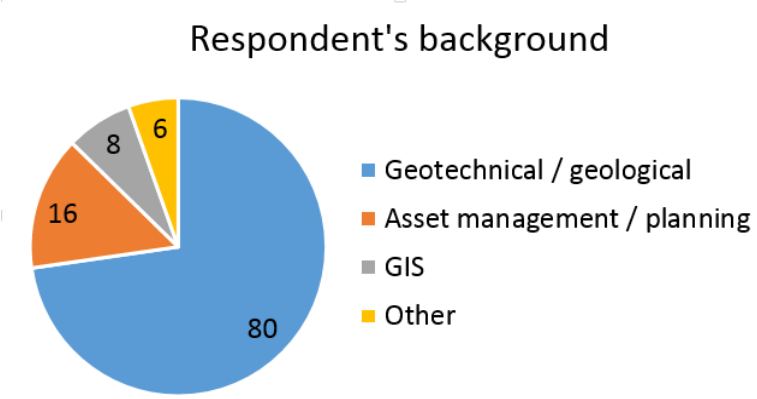


**Figure 2.2:** *Background of the respondents. Numbers of responses are show in each sector.*

Geotechnical asset inventories are a fundamental component of geotechnical asset management systems, as discussed in Chapter 1. Asset inventories were reported for different types of assets (see Figure 2.3), and surprisingly only 13.4% of respondents mentioned that their agencies had no inventories at all, although another 8.5% did not know if there were any inventories for geotechnical assets at their agencies.

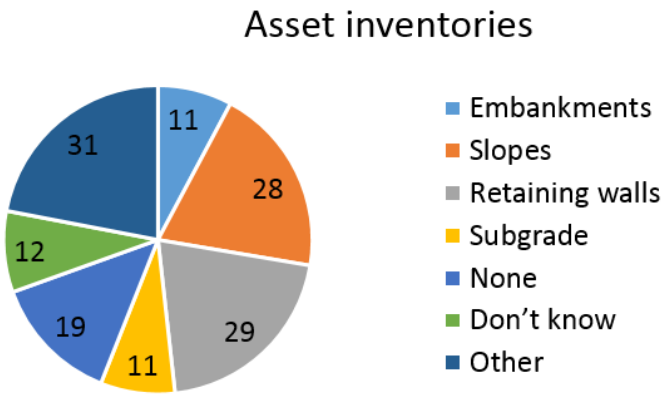


**Figure 2.3:** *Asset inventories for different asset types. Numbers of responses are show in each sector.*

Having such inventories will facilitate the development of a geotechnical asset management system for these agencies, and in some cases such a system may already be in the design of implementation process. The monitoring of assets is crucial for their management, as explained in Chapter 1, and a majority of survey respondents (54.4%) stated that asset

monitoring or intervention was only done when damage or failure was imminent, and only 18.4% reported routine inspections of geotechnical assets (see Figure 2.4).

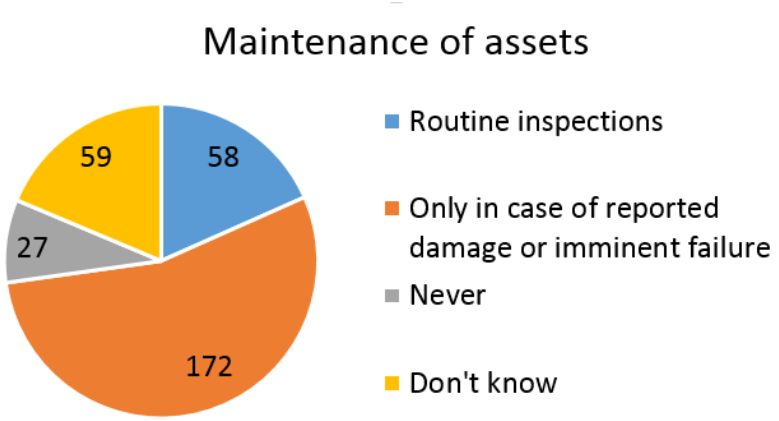


**Figure 2.4:** *Reasons given for asset intervention. Numbers of responses are show in each sector.*

For those cases in which data are being collected on geotechnical assets (67.1%) the main data collection method (33.8%) is by visual inspection, and only 17.1% of respondents reported the collection of some form of deformation data to monitor geotechnical assets (see Figure 2.5).

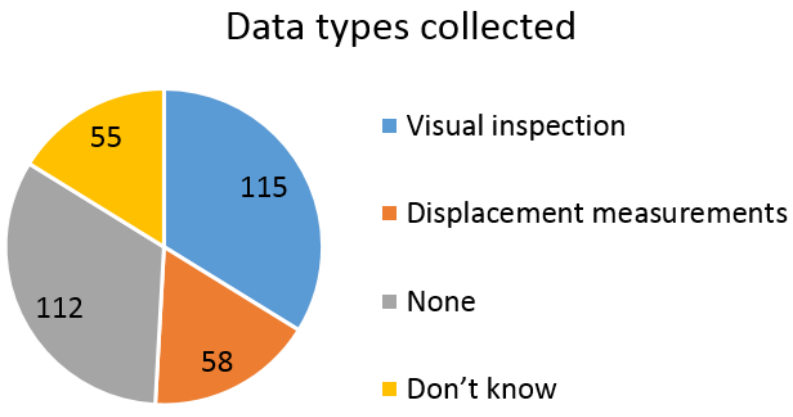


**Figure 2.5:** *Data types collected for each asset. Numbers of responses are show in each sector.*

Analyzing the data was done by an engineer or an expert in the majority (68.1%) of cases, and only 12.1% of responses mentioned some form of GIS tool or decision support system for the analysis of data (see Figure 2.6).

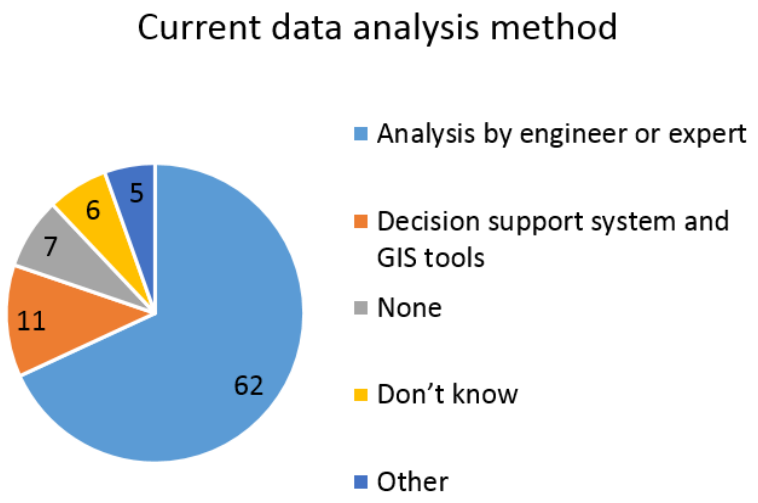


**Figure 2.6:** *Currently used data analysis methods. Numbers of responses are show in each sector.*

Regarding the perceived needs for geotechnical asset management activities, the priority of data collection in the near future was heavily focused on visual inspections (35.5%), although a significant number of respondents (27.6%) chose displacement measurements as a priority data type to be collected in the future (see Figure 2.7).

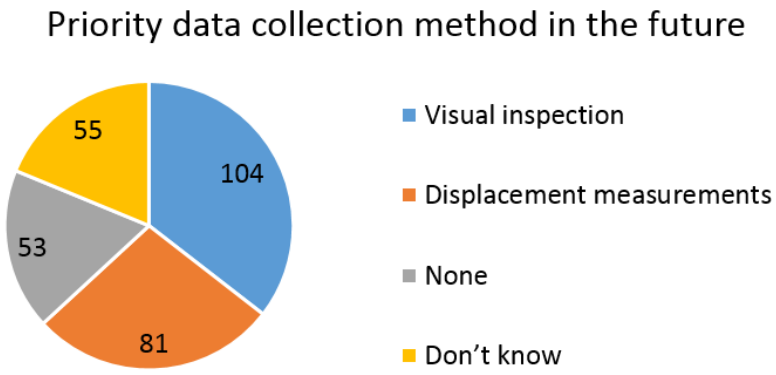


**Figure 2.7:** *Data collection methods seen as the next priority to further develop in the future. Numbers of responses are show in each sector.*

A lack of material or financial resources was the most common (32.6%) reason chosen by survey respondents as a current limitation on geotechnical asset monitoring, although a lack of perceived need was also chosen as a frequent reason (26.3%) by survey respondents (Figure 2.8).

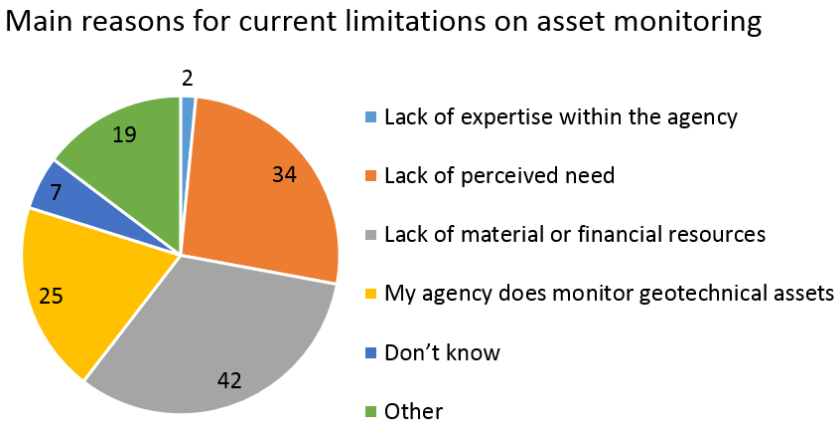


**Figure 2.8:** *Reasons listed as the main limitation to implement geotechnical asset monitoring. Numbers of responses are show in each sector.*

Open ended questions at the end of the survey allowed respondents to express more general views on the topics covered. Details about the current limitations and how the resources available have to be prioritized we sometimes expressed by respondents, for instance:

> "*Geotechnical assets have been not typically been given as much attention as pavements and structures, perhaps as these works tend to degrade less or have fewer serviceability issues. Most asset management is linked to high risk or hazard inventories (areas at risk of scour, landslide, etc.). MnDOT keeps track of the performance (by instrumentation) of critical projects [centralized], but most 'typical' geotechnical features are monitored by District maintenance forces.*"

Despite limitations in funding, some respondents expressed optimism in developing GAM capabilities in the near future, for example:

> "*We have been thwarted in our previous attempts at securing funding for GAM; but there are indications we may a break-thru soon for our walls inventory & insp.*"

Some respondents mentioned ongoing and future GAM components implementation, for instance:

> "*Our agency is working on a retaining wall inventory system and planning to incorporate rockfall inspection and inventory into a more encompassing geohazard management plan that includes performance measures for rockfall, rockslides, landslides, debris flows, sink holes and embankments.*"

Remote sensing was also viewed by some respondents as a potentially useful tool for monitoring geotechnical assets:

"*Remote sensing techniques offer opportunity to monitor geohazard sites much more frequently and efficiently.*"

## 2.3. Conclusion

The central objective of the survey was to investigate current geotechnical asset management practices by transportation agencies, as well as their perceived needs and limitations in that topic. Although many agencies have inventories for some types of geotechnical assets, comprehensive inventories covering all assets are not common. Existing partial inventories are a first step in the process of establishing a GAM system, and further efforts need to be built around those preliminary inventories.

Asset monitoring (e.g., inspection) and maintenance are mainly done in a reactive way, once the assets are in obvious and urgent need for such evaluations, and possibly repair or replacement. When data are collected, the most common method is to do a visual inspections, although some respondents reported that displacement measurements are also done in some cases. Most of the time the data collected on geotechnical assets are analyzed by an engineer or an expert, and only in a few cases where GIS tools and decision support systems reported as analysis tools.

Despite this, a majority of respondents mentioned visual observations as the most common method of data acquisition to be prioritized in the future, but a significant number of respondents also mentioned displacement measurements as a method to be prioritized in the future. The most often reported limitations for asset monitoring, where the lack of material and financial resources, followed by the lack of perceived need.

Providing transportation agencies with cost effective methods for data collection and analysis, may change the current practice and enhance the adoption of asset monitoring methods that are necessary for geotechnical asset management.

## Chapter 3: Identification of Remote Sensing Technologies

### 3.1 Introduction

Transportation asset management (TAM) is a widespread approach for maintaining transportation infrastructure throughout their life-cycle, from construction and inventory creation through preservation and failure mitigation (AASHTO, 2011; Cambridge Systematics Inc., 2002). TAM characteristics may easily be applied to geotechnical assets in the form of geotechnical asset management (GAM) (Vessely, 2013). Assets included in a full-fledged GAM program include, but are not limited to, embankments, cut slopes, natural slopes, and earth retaining walls/structures (Anderson et al., 2008; Stanley & Pierson, 2013).

Similarly, GAM incorporates asset data collection for condition assessments and performance monitoring. A complete geotechnical site investigation usually requires in situ measurements, acquisition of material samples, laboratory tests and analyses, site characteristic modeling, and data interpretation in order to predict the most likely future behavior of each asset. In-depth field-based data collection and analysis is more expensive and will require a larger workforce. These financial and temporal requirements apply additional constraints to the limited resources of transportation agencies and, therefore, complete geotechnical site investigations may not be performed on a regular basis.

Remote sensing-based methods can provide an intermediate level of information between each site investigations. Remote sensing allows for higher frequency data collection (greater temporal resolution) over large areas and usually automated (e.g., acquisition of satellite imagery requires no work on the part of a transportation agency). The tradeoff is remote sensing data are of lower spatial resolution, less robust, and are limited by preset geometric viewing angles when compared to on-foot site investigations. Examples of the application of remote sensing techniques to GAM programs are numerous, but many do not focus on how obtained products may be integrated into the GAM framework, mainly with asset condition assessment and long-term asset monitoring. We propose that surface displacement derived from remotely sensed data can be used as a quantitative indicator of the life-cycle health of example geotechnical assets.

### 3.2 Remote Sensing Techniques

A brief synopsis of the three remote sensing techniques used in this study (InSAR, LiDAR, and optical photogrammetry) is given here. For a complete theoretical overview, please refer to Deliverable 2-A in the Appendix.

#### 3.2.1 Interferometric Synthetic Aperture Radar (InSAR)

InSAR is an active microwave remote sensing technique. There are two basic categories of InSAR techniques: (1) N-Pass InSAR and (2) InSAR Stacking. N-Pass InSAR uses a small number of radar images (usually 2-4) while InSAR Stacking utilizes a stack of radar images (>20); both techniques can be used to monitor ground deformation within the acquisition timespan (Massonnet et al., 1993; Massonnet et al., 1995). Ground deformation is measured by calculating the phase change between images. The phase is a physical characteristic of radar backscatter and can be converted into the change in distance between the sensor and the ground target, or, in other words, deformation rate of the ground target.

InSAR Stacking is used for the measurement of small ground deformation rates (mm/year-scale) because, similar to other geophysical methods (e.g., seismic), stacking allows for an increase in the signal-to-noise ratio (SNR) of the acquired data. One of the two interferometric stacking techniques used in this study is Persistent Scatterer Interferometry (PSI). The PSI processing procedure incorporates all of the processing steps described above, but the output differs. This technique searches the input radar images for pixels with consistently high coherence throughout a stack of 20 images or more. A pixel with consistent coherence usually exhibits a relatively stable geometry (no spatial or temporal decorrelation) and a surface that allows for a great amount of radar backscatter to return to the satellite sensor (echo). Targets that generally fulfill these requirements are usually anthropogenic structures, such as roads, bridges, buildings, and dams. They may also be natural features, such as rock outcrops or cliff faces that lack vegetation. Targets with consistently high radar returns are known as persistent scatterers (PS) and are the only points with ground displacement information in the PSI output. All other non-PS pixels are discarded and provide no information (Ferretti et al., 2000; Ferretti et al., 2001). The second interferometric stacking technique used in this study is Distributed Scatterer Interferometry (DSI). DSI addresses the fourth limitation of PSI (addressed in the previous section), which is that the PSI technique may yield thousands of PS/kilometer in urban areas, but

only tens of PS/kilometer in rural or vegetated areas. Using DSI, we are able to locate distributed scatterers (DS) that give us exactly the same information that PS do (e.g., ground velocity), but DSI is applicable in rural and vegetated regions (Ferretti et al., 2011).

### 3.2.2 Light Detection and Ranging (LiDAR)

LiDAR is an active remote sensing technique. A light pulse is emitted from a laser sensor, reflects off an object, and returns back to the sensor to determine the time of flight of the laser pulse. The time of flight is used to calculate the distance from the sensor to the object. Multiple datasets acquired at the same location but at different times may be used to calculate changes in distance; any changes in distance imply movement of the objects being observed. The distance of the LiDAR sensor from the feature being imaged determines the density and resolution of the LiDAR data being collected. Close range laser scanning collects dense, high resolution data. Aircraft mounted LiDAR sensors collect relatively sparse data, but over much larger areas with great efficiency, compared to static terrestrial LiDAR scanners. As with other remote sensing technology, LiDAR has seen increases in data collection rates and more dense data sets.

The LiDAR data collected is often described as a point cloud. The point cloud has three-dimensional position measurements for the features being scanned. Besides the features of interest on slope, there are other types of data in the point cloud, such as cars on a road, people on a sidewalk, houses, trees, and even the branches and leaves on a tree. To make the LiDAR data in the point cloud useful, the data must be processed and filtered. Many LiDAR vendors provide processing data, however third-party software is usually required for the filtering of data to derive various LiDAR data products. Filtering airborne data is performed by looking down at the data from the perspective of the aircraft – and these filtering algorithms were some of the very first developed to remove features above the ground in order to extract a bare earth data set. Filtering terrestrial data, from a moving vehicle or a static tripod is more involved because the filtering algorithms are not mature for the various applications that the LiDAR data can be used. For geotechnical analysis, it is typical to remove vegetation in order to measure the bare earth.

Accuracy and precision of the LiDAR scan data vary with the LiDAR system and its platform. Distance of the LiDAR scans affects accuracy largely because of the humidity and temperature of the atmosphere that attenuates and diffracts the laser energy as the laser passes

through the air. Also, the GNSS, and INS referencing affect the accuracy of the LiDAR data. It is important to note that INS are especially susceptible to a type of error called drift, which adds a cumulative error until the drift is corrected in a calibration process after the data is collected.

### 3.2.3 Optical Photogrammetry

Optical photogrammetry is a passive remote sensing technique. Optical remote sensing is most commonly done by using sensors that are sensitive to the visible portion of the electromagnetic spectrum. This corresponds to wavelengths of light are between 400 and 700 nm. Optical systems are able to detect near infrared wavelengths of light (approximately 700 to 1300 nm or 1.3 microns) but use filters to prevent them from being detected by the sensor; however, digital cameras can have their filter removed. The most common optical sensors are Charge-Coupled Devices (CCDs), which are used in typical consumer-grade digital cameras. The wide scale availability of digital cameras and low cost make them a good candidate for characterizing remote sensing applications. These sensors have been developed to be smaller as they are used for cell phone cameras as well as in professional photography.

Photogrammetry is "the science or art of deducing the physical dimensions of objects from measurements on photographs of the objects" (Henriksen, 1994). This includes measurements made from both film and digital photography. Digital photogrammetry has been demonstrated as a viable technique for generating 3D models of structures and structural elements (Maas & Hampel, 2006). In order to perform 3D photogrammetry, the photos need to be taken with at least a 60% overlap (McGlone et al., 2004). This ensures that a feature on the ground is represented in at least two photos. At distances closer to the surface than traditional aerial imagery this technique is more specifically called close-range photogrammetry. Close-range photogrammetry is defined as capturing imagery of an object or the ground from a range of less than 100 m (328 ft) (Jiang et al., 2008). Typically, 3D models are generated by using the bundle adjustment principle (Triggs et al., 2000). This process used determines the orientation of each image in a series of overlapping images to generate a sparse point cloud (Triggs et al., 2000). This process allows for images to be taken at different angles, which occurs when the camera rolls and changes pitch as it is moved across its target.

### 3.3 Requirements for Remote Sensing Techniques when Applied to GAM: What to Consider Prior to Data Acquisition

There are many site-specific considerations required for optimal use of InSAR, LiDAR, and optical photogrammetry. Each remote sensing technique has its advantages and limitations; these must be acknowledged and understood prior to data analysis, or the user may be surprised by the results. An in-depth discussion of all considerations is not discussed here – that may be found in the literature. Instead, a concise list of general requirements for each technique is listed below.

InSAR

1. PS/DS point locations are unknown prior to processing. Due to the slant-range nature of synthetic aperture radar acquisition, there is a possibility that some geotechnical assets will not be observed by the radar sensor (this is especially the case in mountainous terrain). Therefore, unfortunately, PSI and DSI will be unable to measure ground deformation on these geotechnical assets.
2. Topography and satellite view angle will dictate the number of geotechnical assets visible and analyzable. The shadow effect, where areas of topographic high will block a satellite sensor's view of lower topography behind the peak, is common in mountainous terrain and results in areas of data loss. Shadow zones can be located, but no data is retrievable.
3. The geometry of the geotechnical asset with respect to the satellite view direction dictates how much of the asset, if any at all, is viewable from the sensor. Ideally a geotechnical asset will be in the direct line-of-sight of the radar sensor (single reflection) or in a geometrically advantageous position where the sensor can view the asset through multiple bounces (multiple reflections).
4. The amount and type of vegetation impacts the number of PS/DS points available on and/or around a geotechnical asset. Coherence is inversely proportional to the amount and density of vegetation, with high amounts of vegetation and/or dense (thick) vegetation resulting in a low coherence, which means a lower likelihood of PS/DS points occurring in that area.
5. If the ground motion exceeds one-half the radar wavelength between each acquisition, the geotechnical asset will decorrelate and no information can be gained. Ways to avoid this

problem are to (1) acquire enough radar images close together temporally, (2) process imagery from longer wavelength sensors, or (3) avoid trying to monitor geotechnical assets with relatively high displacement rates.

6. Although radar penetrates clouds, it is affected by variations in moisture content in both the atmosphere and on/in the ground. The best conditions for radar acquisition are when there is low atmospheric variability and moisture content and the ground moisture content is consistent at each acquisition date.
7. Depending on the size of the geotechnical asset network (area of interest), multiple stacks of radar imagery (with 20+ images per stack) may be required for PSI/DSI processing.
8. Image coverage varies throughout the world because the space agencies have different areas of interest. Check online catalogs from respective space agencies to see spatial and temporal coverage.

LiDAR

1. Mobile LiDAR is much more efficient at acquiring data on the regional scale, compared to terrestrial LiDAR which works well at the site-by-site level. Terrestrial LiDAR is superior in data density and accuracy, but mobile LiDAR allows for a cheaper and quicker method of acquiring data over large areas.
2. Mobile LiDAR (e.g., airborne or ground vehicle) require precise synchronization and calibration with GNSS and INS systems. This will reduce position and orientation error caused by INS drift, which is increases with longer survey times. Both horizontal and vertical controls are also required so that the resultant point cloud is projected in a proper coordinate system using an ellipsoid datum.
3. It is difficult to differentiate small-scale features, whether they be geotechnical, geological, or hazard related.
4. Repeated surveys with established ground control can be used to generate in-depth analysis of geotechnical hazards and risks across observable assets. Multiple acquisitions can be used to monitor changes in deformation rates, asset location, asset shape, and other hazardous changes such as erosion, scouring, or weathering.

5. Terrestrial LiDAR surveys are limited to the sensor view angles and, since repeat surveys require the LiDAR to occupy the same position each time, shadow zones will never be visible.

Optical Photogrammetry

1. Aerial optical photogrammetry – imagery acquired using satellite, airplane, or unmanned aerial vehicle (UAV) – allow for the rapid assessment of geotechnical assets over a large area.
2. Since this is a passive technique, optical imagery can only be acquired during the day and, using aerial vehicles, when there is no cloud cover. Other obvious obstructions, such as snow or vegetation, will also lessen the effectiveness of optical photogrammetry. The time of day is also critical, as lighting variations could introduce glare in the optical image which will affect processing results.
3. Weather remains the largest factor of successful data collection for aerial vehicles, especially for UAVs which are easily affected by turbulence and adverse weather conditions (e.g., precipitation).
4. Resolution is directly proportional to the distance from the asset. A higher resolution results in less coverage, and vice versa.

### 3.4 Remote Sensing Technologies Rating

A relative rating to compare the effectiveness of InSAR, LiDAR, and optical photogrammetry was performed using the method suggested by Ahlborn et al. (2010). The rating is based on the perceived performance with respect to GAM of these three techniques. A series of performance criteria were defined and a score for each criterion was chosen based on the evaluation method, with a score of 1 meaning *least adequate at meeting the criterion* and 3 meaning the method *fully meets the criterion*. Seven criteria were selected based on a GAM literature review (Anderson et al., 2008; Stanley et al., 2013; Vessely, 2013). The criteria are:

1. **Information Content.** How relevant is the information gained from each technique towards GAM?
2. **Spatial Density and Ground Resolution.** How many data points are acquired over one image pixel?

3. **Data Availability and Revisit Time.** How many images are available and how often are images acquired?
4. **Accuracy.** How do the data acquired by remote sensing techniques compare to in situ and field measurements (ground-truthing)?
5. **Direct Cost for Data Collection and Analysis.** How much does it cost to acquire, process, analyze, and interpret the data collected by the remote sensing technique?
6. **Indirect Cost for Data Collection and Analysis.** How much does it cost to purchase the instruments and train staff to acquire data?
7. **Availability of Historical Data.** How far into the past are relevant data available and usable for the technique?

Table 3.1 shows the results of the remote sensing technologies rating. InSAR outperforms the other techniques with respect to the direct cost for data collection and analysis (which, for educational purposes, can be free with acceptance of a proposal) and availability of historical data. Optical photogrammetry outperforms the other techniques with respect to the indirect cost for data collection and analysis. LiDAR, although not outperforming all other techniques in any one given category, posts solid scores in four of the seven categories, including the data's spatial density/ground resolution and data availability and revisit time.

***Table 3.1:*** *Performance ratings*

| **Criteria** | InSAR | LiDAR | Optical Photogrammetry |
|---|---|---|---|
| Information Content | 3 | 3 | 3 |
| Spatial Density and Ground Resolution | 2 | 3 | 3 |
| Data Availability and Revisit Time | 2 | 3 | 3 |
| Accuracy | 3 | 3 | 3 |
| Direct Cost for Data Collection and Analysis | 3 | 2 | 2 |
| Indirect Cost for Data Collection and Analysis | 3 | 1 | 3 |
| Availability of Historical Data | 3 | 1 | 2 |

### 3.5 Conclusion

Geotechnical assets, such as retaining walls, embankments, cut slopes, and rock slopes are indispensable components for healthy transportation infrastructure. According to the American Association of State Highway and Transportations Officials' (AASHTO) Transportation Asset Management Guide, over the past decade there has been a growing awareness that the current methods of transportation infrastructure management are not adequate to meet the demands of the public and therefore, need improvement (AASHTO 2013).

Current practices for managing geotechnical assets along transportation corridors are mostly focused on restoring the asset after failure, as opposed to identifying and remediating hazardous conditions before their occurrence. One of the reasons for lacking a proactive system is, geotechnical assets are extensive and assessing their condition using traditional site inspection is mostly qualitative and laborious.

The applicability of three remote sensing techniques (InSAR, LiDAR, and Photogrammetry) were rated for geotechnical asset management based on different criteria. Results indicate that there is no technique that has high rating for all criteria. In general, the photogrammetry method is the most cost effective and easy to process, whereas, the InSAR method has the relatively low cost per $km^2$ and can provide mm scale accuracy. The LiDAR and photogrammetry are comparable except that the initial cost for LiDAR instrumentation can be significantly higher. The detailed rating results presented in Table 3.1 highlight the criteria of the remote sensing techniques that have potential to impact the current practices for geotechnical asset management, and also the ones that need additional sensor development and commercialization. Ongoing and future activities of this study will investigate the field performance of these remote sensing techniques for geotechnical asset management.

# Chapter 4: Field Verification and Evaluation of Remote Sensing Technologies Applied to Geotechnical Asset Management

The different remote sensing technologies identified to have potential for monitoring and assessment purposes within a geotechnical asset management system, as described in chapter 4, were tested for performance and applicability to specific asset management tasks. The ability to use remote sensing to measure surface deformation over time was particularly relevant for such technologies. This chapter summarizes the extensive field verification and evaluation of the remote sensing technologies, as applicable to different geotechnical asset monitoring scenarios.

## 4.1 Description of Test Sites

Field and laboratory test sites were chosen at different locations, and included a variety of geotechnical asset types, including retaining walls, and natural and artificial slopes in rock, soil and permafrost environments. Three different field locations in Michigan, Nevada and Alaska were chosen for field site testing. Assets were located in different types of transportation corridors, including highways, railroads and pipelines. Laboratory testing on scaled models of retaining walls was also performed.

### 4.1.1 M-10 Highway, Detroit, Michigan

A series of retaining walls on M-10 highway in Detroit, Michigan, were chosen to test remote sensing methods for surface displacement measurements. The retaining walls were near the junction between the M-10 highway and Meyers Road (see Figure 4.1). At the test location the M-10 is a depressed highway with three traffic lanes in in each direction, confined by 16 feet tall, vertical cantilever retaining walls, separated in 100 feet sections. Parallel running service drives are located on top the fill behind the retaining walls. Retaining wall sections move independently in response to stresses.

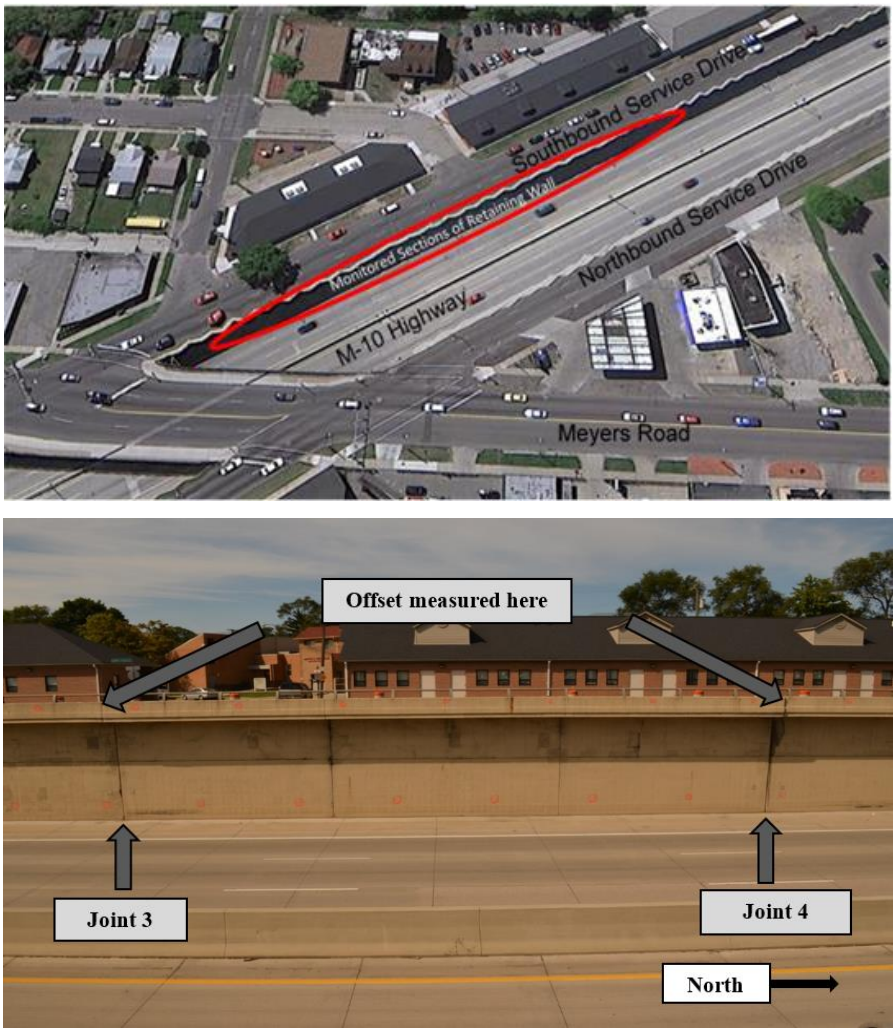


***Figure 4.1***. *Upper panel, location of the retaining walls along M-10 highway, Detroit, Michigan. (Taken from Cerminaro, 2014). Lower panel, picture of the retaining walls.*

The retaining walls were designed and build in the 1950's and 1960's, using tension tie-backs to increase wall stability to overturning and reduce wall footing size (Jasson, 2013). In the original design the tie-backs were specified as cables but were changed to solid bars in the actual construction, and this change, coupled with back-all drainage problems is believed to have led to the wall failure (Cerminaro, 2014). Significant movement between retaining wall sections, up to 8 cm, was observed at the site, leading to the replacement of some sections.

### 4.1.2 Railroad Corridor in Nevada

A railroad corridor section of approximately 30 km in Nevada was chosen as test site for monitoring surface movement on rock slopes. This site included several known rock slide locations, which had shown significant slope movement in recent times. The railroad corridor is located within a series of steep sided canyons throughout most of the 30 km stretch, with rock slopes composed of old volcanic materials. Bouali et al. (2016a) give a detailed description of this site.

A regional scale analysis of the 30 km railroad corridor focused on methods to identify potential unstable slopes at a large scale. At a local scale, a few particular slopes were examined in more detail, using remote sensing methods that would only be applicable at smaller scale targets. Figure 4.2 shows some of the rock slopes chosen to test such remote sensing methods.

***Figure 4.2:*** *Slopes chosen to perform detailed work due to large displacements and instabilities.*

### 4.1.3 Trans Alaska Pipeline Corridor

The Trans-Alaska Pipeline System was targeted for selection of field testing sites, particularly at steep slopes on permafrost soil (Figure 4.3). Out of six initial sites identified for potential fieldwork, two locations, Treasure Creek and Lost Creek, were chosen for in-depth analysis of slope movement measurements using remote sensing methods. An additional site near the highway (and pipeline) bridge over the Yukon River was also added for in-depth analysis later on, despite the availability of ground control points.

Treasure Creek and Lost Creek are located on steep permafrost slopes, exceeding 20º in some places, and have recently shown significant movements, in excess of 1 m at some

locations. Slumping, cracking and other surface deformation features at the sites were observed during fieldwork, reflecting such significant movements.

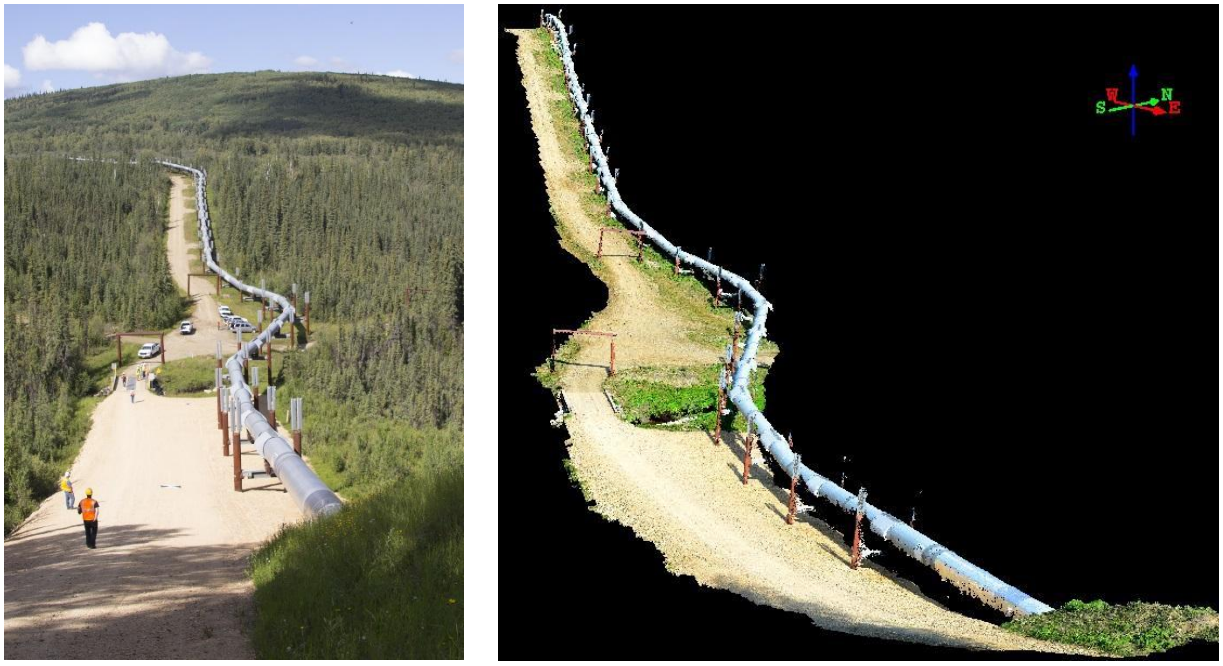


***Figure 4.3:*** *Treasure Creek pipeline section in Alaska. Left panel shows the view down a steep slope along the pipeline. Right panel shows the same area as seen I the left panel, but reconstructed from the photogrammetric point cloud.*

### 4.1.4 Laboratory-scaled Model Setup

Controlled tests in a laboratory setting were also performed on scaled models of retaining walls. A model setup which mimicked two adjacent retaining wall sections that presented differential movement was designed and build out of wood and Styrofoam (see figure 4.4). Two boards, 8 feet tall by 4 feet wide were mounted on hinges to allow vertical tilting, simulating retaining wall rotation. Board sections are mounted on independent structures which allows any type of differential movement between both sections to be modeled. The system is mounted on wheels and can be displayed indoors and outdoors, to simulate different lighting conditions. Different texturing types of the Styrofoam boards was also included in the experimental setup.

***Figure 4.4:*** *Scaled models build to represent retaining wall movements in the laboratory.*

### 4.2. Description of Data

Datasets analyzed in this project include data collected during its execution, but also data collected previously by project partners or other agencies. InSAR and LiDAR datasets spanning several years were analyzed, and additional LiDAR and photogrammetric data were collected during the project. Here we summarize these datasets, and refer to reader to the appendices for more detailed information.

#### 4.2.1 InSAR Datasets

We used moderate ground resolution InSAR satellite data (30 m) and wavelength (C Band - 5.6 cm), and Table 4.1 summarizes the different types of available datasets. Of all the available datasets listed on Table 4.1, only subsets from a few were employed in the analysis, as will be described in the corresponding section. Datasets were chosen to allow for the use of staking techniques like PSI, as this allowed for points in relatively low coherence areas to be analyzed, as discussed in the results section.

***Table 4.1:*** *List of historical, present, and future InSAR-compatible satellites.*

| Satellite | Mission Timespan | Revisit Period (days) | Ground Resolution (meters) | Radar Band* | Organization | Price Per Image (US Dollars)** | |
|---|---|---|---|---|---|---|---|
| | | | | | | Commercial | Research |
| ERS-1 | 1991 - 2000 | 35 | 25 | C | European Space Agency (ESA) | $212 - $354 | FREE |
| JERS-1 | 1992 - 1998 | 44 | 18 | L | Japan Aerospace Exploration Agency (JAXA) | | FREE (limited) |
| ERS-2 | 1995 - 2011 | 35 | 25 | C | ESA | $212 - $354 | FREE |
| RADARSAT-1 | 1995 - 2013 | 24 | 10-100 | C | Canadian Space Agency (CSA) | $3,047 - $3809 | FREE |
| ENVISAT | 2002 - 2013 | 35 | 25-150 | C | ESA | $354 - $591 | FREE |
| ALOS PALSAR | 2006 - 2011 | 46 | 7-100 | L | JAXA | $42 - $709 | FREE |
| RADARSAT-2 | 2007 - | 24 | 3-100 | C | CSA | $3,047 - $7,110 | |
| COSMO-SkyMed | 2007 - | 16 | 1-100 | X | Italian Space Agency (ASI) | $680 - $2,268 | |
| TerraSAR-X | 2007 - | 11 | 1-16 | X | German Aerospace Center (DLR) | $875 - $7,972 | |
| TecSAR | 2008 - | 14 | 1-8 | X | Israel Aerospace Industries | NA | |
| Meteor-3M | 2009 - | 3 | 400-1,000 | X | RosHydroMet | $30/$40 - ? | |
| RISAT-2 | 2009 - | 14 | 1-8 | X | Indian Space | NA (contact Antrix) | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | Research Organization (ISRO) | | |
| TanDEM-X | 2010 - | 11 | 1-16 | X | DLR | NA | $118 |
| RISAT-1 | 2012 - | 25 | 1-50 | C | ISRO | NA (contact Antrix) | |
| HJ-1C | 2012 - | 1 | 20 | S | NDRCC/SEPA of China | NA | |
| KOMPSAT-5 | 2013 - | 28 | 1-20 | X | Korean Aerospace Research Institute (KARI) | NA | |
| ALOS PALSAR-2 | 2014 - | 14 | 1-100 | L | JAXA | $1,257 - $4,191 | FREE |
| Kondor-E1 | 2014 - | 2-3 | 1-30 | S | NPO Mashinostroyenia | NA | |
| Sentinel-1A | 2014 - | 12 | 4-80 | C | ESA | FREE | |
| KOMPSAT-7 | 2014 - | 14 | 1-20 | X | KARI | NA | |
| SAOCOM Constellation | 2015 - | 8-16 | 10-100 | L | Comisión Nacional de Actividades Espaciales | | |
| SEOSAR/Paz | 2015 - | 11 | 1-15 | X | Satélite Español de Observación SAR | Will be publically available | |
| Sentinal-1B | 2016 - | 6 | 4-80 | C | ESA | Will be FREE | |
| COSMO-SkyMed 2nd Generation | 2016 - | 1.5-10 | 1-35 | X | ASI | Will be publically available | |
| TerraSAR-NG | 2017 - | ~0.42 | 0.25-30 | X | DLR | | |
| RadarSat | 2018 - | 3-12 | 3-100 | C | CSA | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Constellation | | | | | | |
| RISAT-1A | 2019 - | 12 | 1-50 | C | ISRO | |
| BIOMASS | 2020 - | 25 | 50-60 | P | ESA | |
| NISAR | 2020 - | | | L, S | NASA & ISRO | |
| DESDynI | ? - | | 10 | L | NASA | |
| SCLP | ? - | | | X, Ku | NASA | |

**P Band (□ = 69 cm); L Band (□ = 23.6 cm); S Band (□ = 9.6 cm); C Band (□ = 5.6 cm); X Band (□ = 3.1 cm); Ku Band (□ = 2 cm)*

***US Dollar exchange rates (January 2015). NA = not available for commercial/educational use. Prices and data availability listed for users in the United States.*

### 4.2.2 LiDAR Datasets

Aerial and terrestrial (static) LiDAR datasets were used for this project. Aerial LiDAR data include publicly available datasets for the Michigan and Alaska sites, as well as aerial dataset collected and made available to us by project partners. Terrestrial LiDAR datasets collected prior to the project at the Nevada site were also made available to us (Figure 4.5), and additional terrestrial LiDAR data were collected for that site during the project. Terrestrial LiDAR data were also collected for the laboratory setup, to compare the results with the photogrammetric methods.

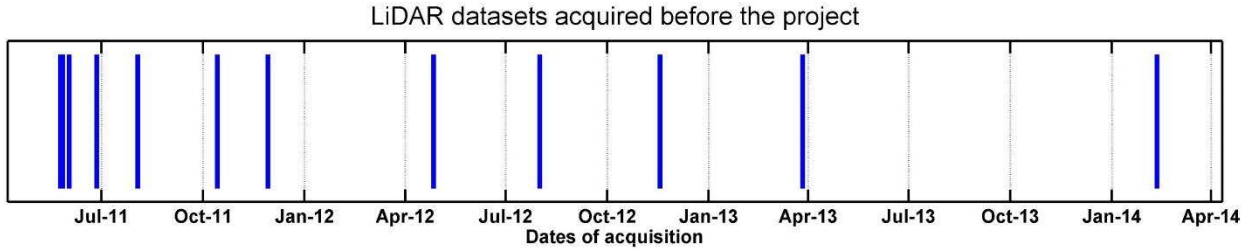


***Figure 4.5:*** *LiDAR acquisition dates for datasets obtained prior to the project at the Nevada testing site.*

Aerial datasets typically have point densities of less than 10 points per $m^2$ and the associated errors are of the order of tens of centimeters. Due to its relatively lower resolution and precision, aerial LiDAR datasets were mainly used for ancillary data purposes (e. g. generation of high resolution DEMs, etc.) that are also necessary for the transportation asset management (Escobar-Wolf et al., 2015, Justice, 2015).

Terrestrial LiDAR datasets have much higher point densities, up to thousands of points per $m^2$ (see figure 4.6), and much higher precision, typically on the order of 1 to 2 cm. Terrestrial LiDAR dataset used for the Nevada site include 11 point clouds acquired between 2011 and 2014 (see figure 4.5), provided by one of the project partners.

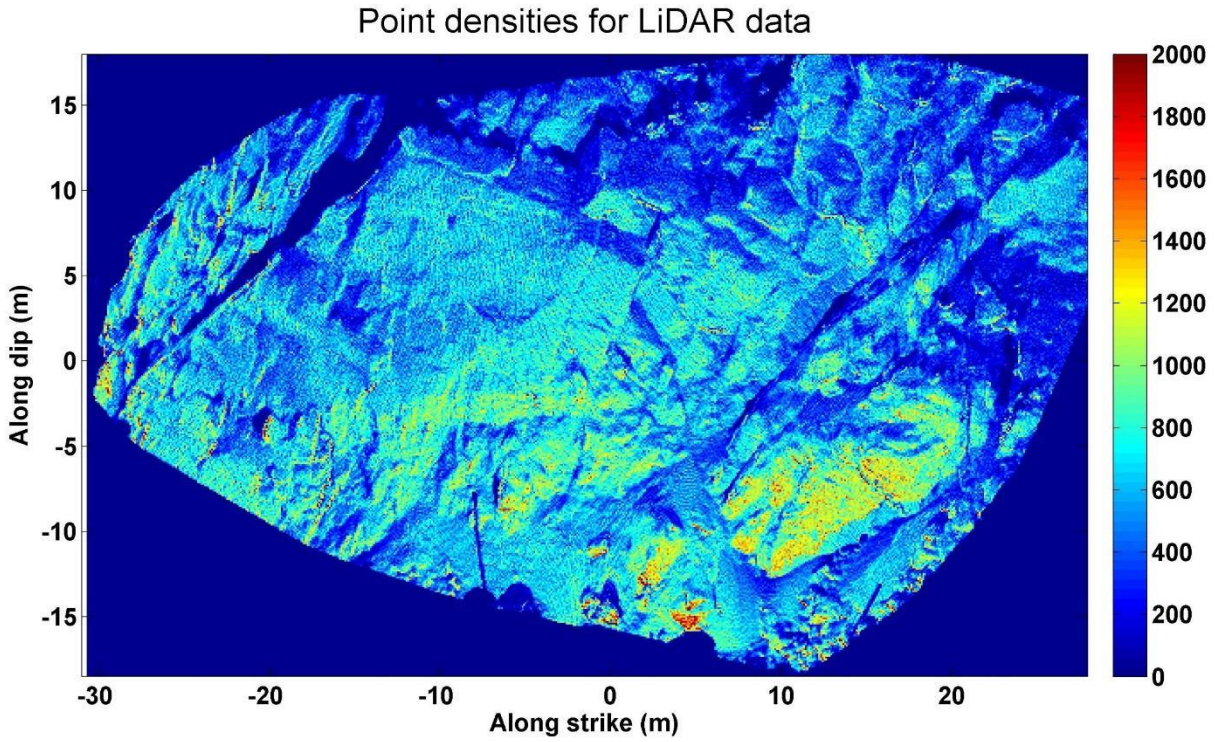


***Figure 4.6:*** *Surface point densities for a rock slope at the Nevada test site.*

### 4.2.3 Photogrammetry Datasets

Photogrammetric datasets (i.e., photographs) were acquired at all field testing sites. Table 4.2 summarizes the photogrammetric datasets collected during the project. Photographs were taken from different platforms, including terrestrial (static and mobile) and aerial (from UAVs and helicopter). Cameras used include DSLR high resolution (16 to 36 megapixel) cameras, with

35 to 55 mm optical lenses, and data acquisition plans were designed to maximize photographic overlap and redundancy. A cinematographic camera was also used to test high speed terrestrial mobile data acquisition.

***Table 4.2:*** *List of field sites where digital photogrammetric data were acquired between 2014 and 2015. The platform for the data acquisition is also indicated.*

| **Site or location** | **2014 field work** | | | **2015 field work** | | |
|---|---|---|---|---|---|---|
| | **Helicopter or UAV** | **Terrestrial** | **Mobile** | **Helicopter or UAV** | **Terrestrial** | **Mobile** |
| Treasure Creek, Alaska | x | x | x | x | x | x |
| Lost Creek, Alaska | x | x | | x | x | |
| Dalton Highway landslide site, Alaska | x | | | x | | |
| Dalton Highway Yukon Bridge, Alaska | x | | | x | | |
| Delta Bridge, Alaska | | | | x | | |
| Glitter Gulch, Alaska | | x | x | x | x | x |
| Nevada test site, location 1 | x | x | x | x | x | x |
| Nevada test site, location 2 | | | | x | x | |
| Hill Street, Cincinnati, Ohio | x | x | x | x | x | x |
| Elboran Street, Cincinnati, Ohio | x | x | x | x | x | x |
| Laboratory scaled model setup | | x | | | x | |
| Michigan Tech Campus walls | | x | | | | |

Photogrammetry data acquisition was done in the field in 2014 and 2015 at the Michigan, Nevada, and Alaska sites, using aerial (UAV's and helicopter) and terrestrial (static and mobile) platforms. Ground control was either provided by project research partners or collected in the field and laboratory experiments, using either a Trimble GeoExplorer GNSS receiver or a total station. Ground control precision estimates put errors at < 10 cm for the GPS surveyed points, and < 3 mm for the total station surveyed ground control. Ground control precision for data provided by research partners varies but is assumed to be similar to that of the total station.

### 4.3. Data Processing and Results

Data processing was focused on measuring surface displacement values of potentially unstable retaining walls and slopes, but additional useful information for the geotechnical asset management process was also extracted in some cases, e.g. high resolution DEMs. Displacement measurements were done by comparing spatial data acquired at different times, such comparison can be between the locations of points at the surface. In the case of LiDAR and photogrammetry the displacement measurement can be done by subtracting the location vector of common points, between datasets acquired at different times. In the case of InSAR this is done by means of interferometry, i.e. by comparing the phase of radar waves reflected by the target surface.

Point datasets, as those provided by photogrammetry, LiDAR and InSAR, are unavoidably incomplete representations of continuous surfaces, and the locations of points in three-dimensional space are also subject to errors. Assessing how well such point clouds represent the real surface, and quantifying the associated errors is crucial, especially when we aim to detect cm to sub-cm magnitude displacements of such surfaces. For these reasons, point surface densities and point location errors estimations are required to assess the quality of the datasets (Sahoo et al. 2007; Shan and Toth, 2008).

#### 4.3.1 InSAR results for the Nevada Test Site

Ninety radar images acquired between August 20, 1992 and August 15, 2010 over the Nevada test site were used in the InSAR analysis, 40 from ERS-1 and ERS-2 satellites and 50 from ENVISAT, corresponding to C-Band SAR antennae sensors operating at a 5.331 GHz frequency. Images had a descending track line-of-sight (LOS) with an azimuth direction of N86°W, and an incidence angle centered at 23º from nadir. Data processing was done using a PSI algorithm within the ENVI SARscape software, and SqueeSAR™ algorithm processing was done by TRE Canada, following the algorithms developed by Tele-Rilevamento Europa (TRE), in a joint PSI-DSI processing. All measurements presented are positive (towards the satellite) and negative (away from the satellite) displacements along the satellite-ground line of site at the time of image acquisition.

Figure 4.7(a) shows PSI results for the Nevada test site. High coherence thresholds, slope geometry and vegetation reduced the number of PS points, but overall the PS results agree with ground observations, showing larger movements in areas where slope instability was observed in

the field. Surface displacement velocities were as high as -2.57 mm/year for the unstable block, while smaller velocities of -0.97 mm/year were measured upslope from the unstable block, and can be contrasted with virtually stable terrain to the north (-0.43 mm/year) and south (-0.97 mm/year). Areas potentially affected by runoff exhibited abnormally high velocities (Runoff A: -3.50 mm/year; Runoff B: -0.86 mm/year in Figure 4.7(b)).

Results from the SqueeSAR™ algorithm (Ferretti et al., 2011) are shown in Figure 4.8, and it becomes apparent that this technique is able to resolve surface displacement for more points. The SqueeSAR™ results show a general agreement with the PSI displacement measurements, with the largest displacements confined to the same unstable block as identified in the PSI results, and smaller displacements measured in the more stable, adjacent terrain.

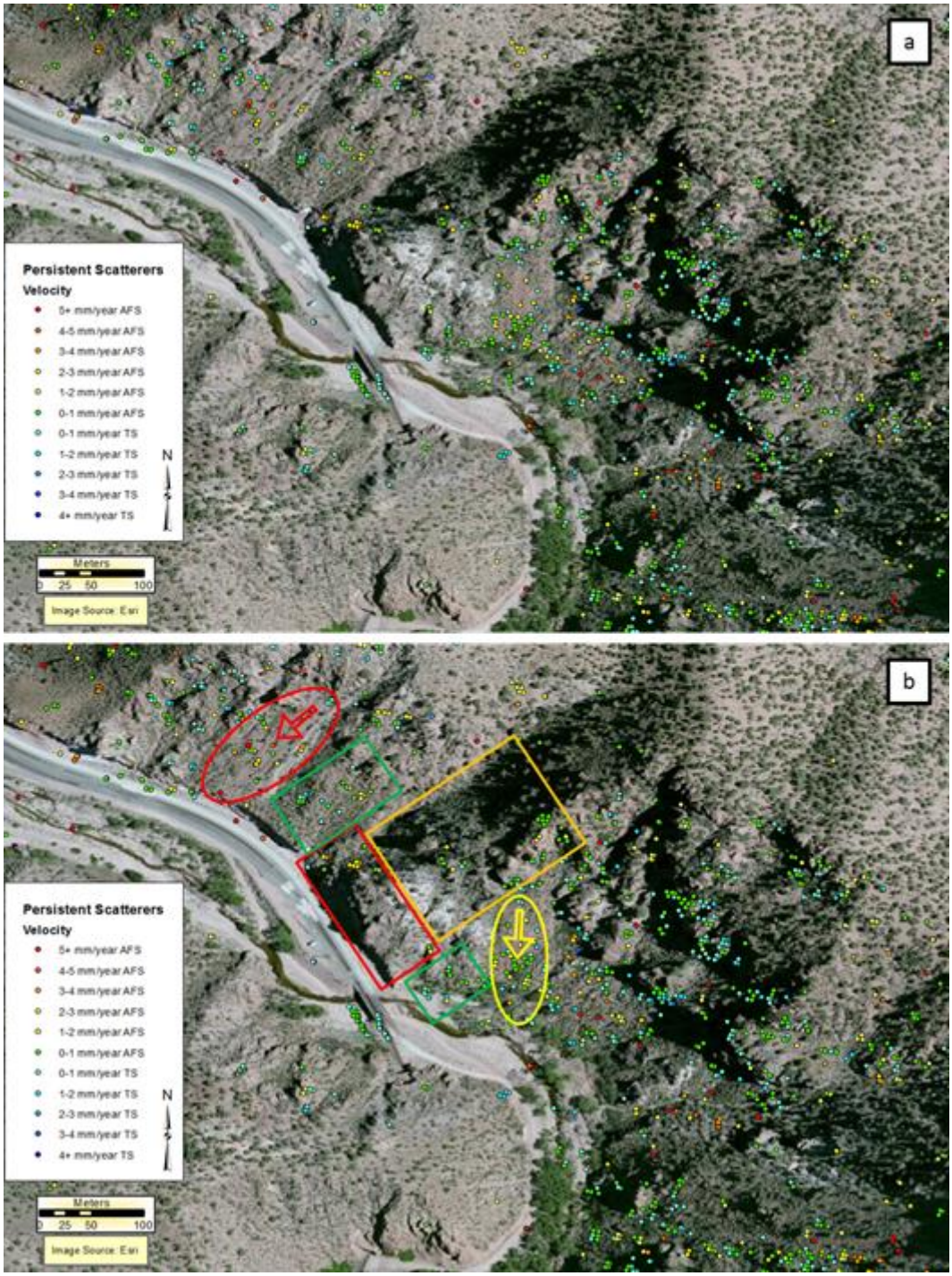


***Figure 4.7:*** *Displacements obtained from InSAR analysis for the Nevada test site. (a) Results from PSI analysis. (b) Segmentation of areas with similar displacement values. The red polygon shows the slope with the highest displacement values. The orange polygon corresponds to intermediate velocities, and the green areas show stable (within the error margins) areas.*


***Figure 4.8:*** *Results from applying the SqueeSAR™ results to the same slopes shown in Figure 4.7.*

Time series plots of displacement from DS point on the unstable slope show surface movement beginning in 2005 (see Figure 4.9), and an apparent previous period of stability going back to 1992. These results are consistent with geotechnical reports and persona communications with the railroad company technicians.

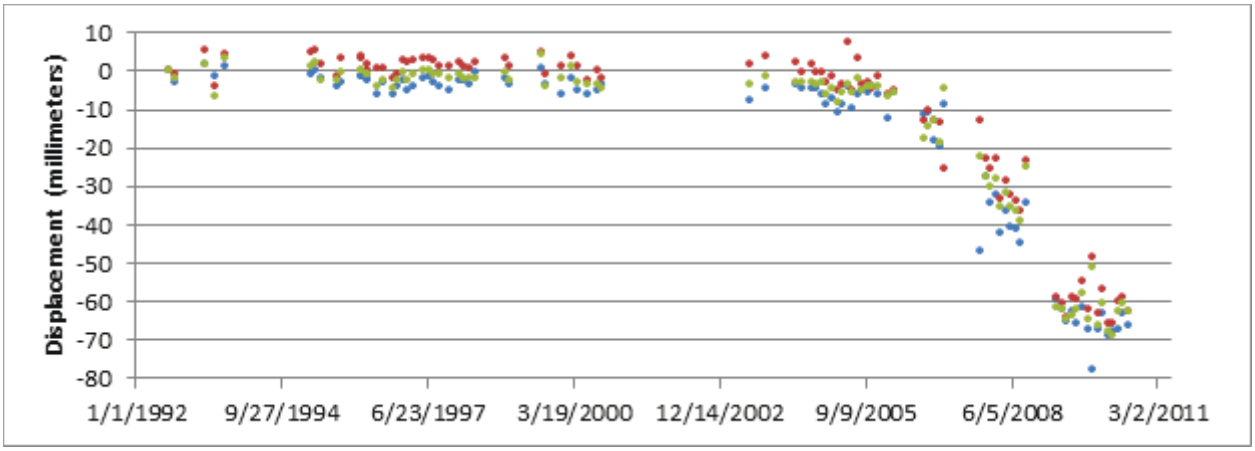


***Figure 4.9:*** *Time-series of measured displacement for the highly unstable slope shown in Figures 4.7 and 4.8 for the three DS points.*

### 4.3.2 InSAR Results for the Michigan Site

InSAR results for the Detroit area test site in Michigan were less successful in showing surface displacement for the retaining walls initially targeted in the project, however other nearby areas did show interesting surface displacement patterns. PSI InSAR analysis of SAR images covering the entire Detroit metropolitan area was accomplished with 50 ERS-1/-2 SAR images covering the 1992 to 2000 period, and revealed a maximum subsidence velocity of 4.2 mm/year and a maximum uplift of 4.0 mm/year for particular pixels in the area (Figure 4.10).

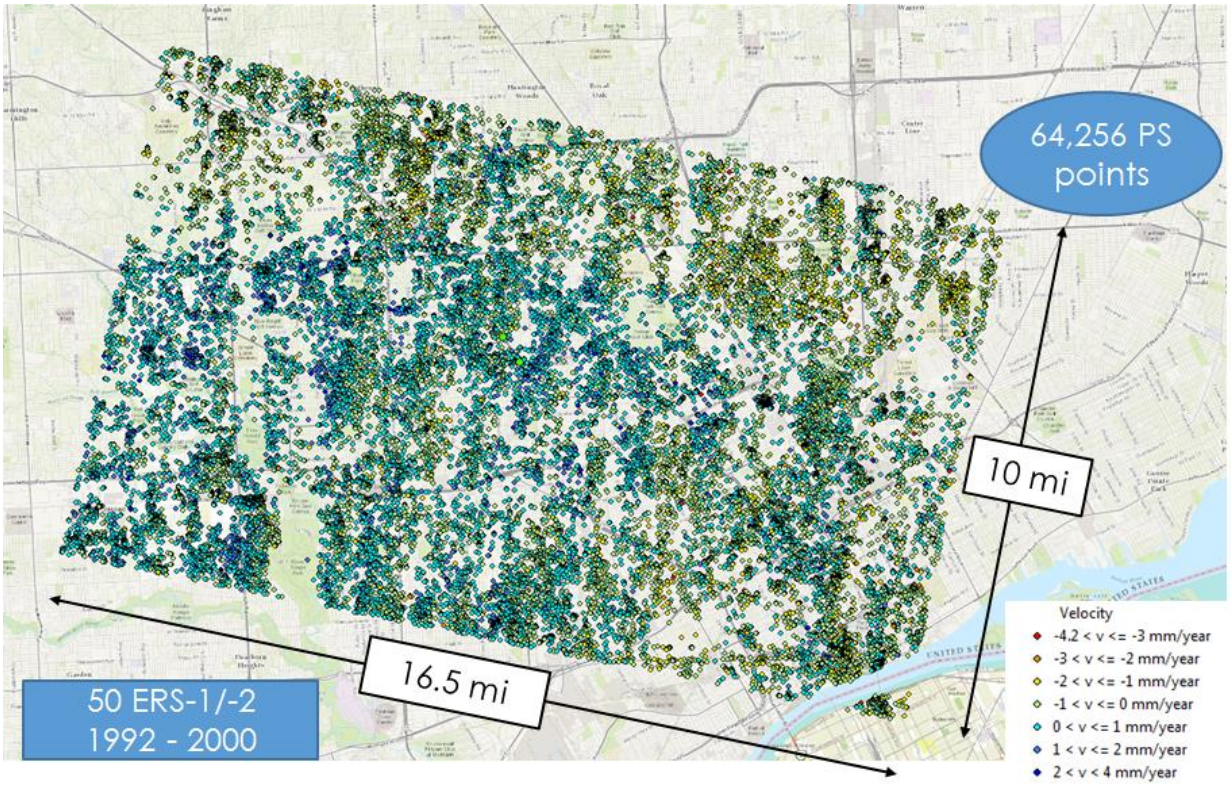


***Figure 4.10:*** *Results from PSI processing for the metropolitan Detroit area.*

### 4.3.3 InSAR Results for the Alaska Sites

Results from InSAR processing for the Alaska sites were mostly unsuccessful (Bouali et al., 2014), with individual interferograms showings low coherence values and even preventing the use of staking techniques. The general low coherence is likely the result of extensive forest coverage and the lack of suitable persistent reflectors along the pipeline corridor.

### 4.3.4 LiDAR Results for the Nevada Test Site

Surface displacements measurements derived from comparing 11 LiDAR datasets acquired between 2011 and 2014 on the unstable rock slope in the Nevada test site, clearly show that significant displacement took period on that slope during the covered time period. Figure 4.11 shows vertical cross sections generated perpendicularly to the rock slope, from LiDAR point clouds acquired at different times, and the outwards slope movement is evident.

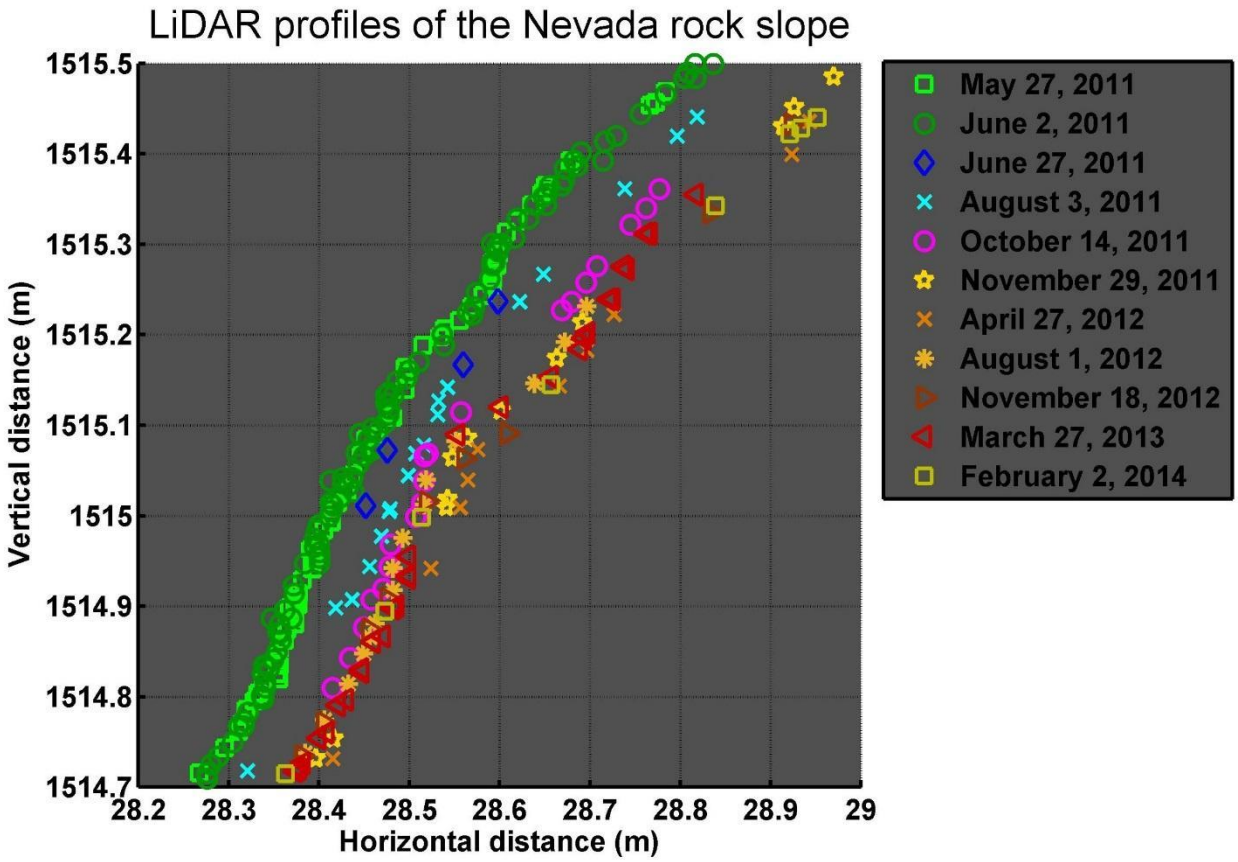


***Figure 4.11**: Vertical profiles derived from LiDAR data for the Nevada test site. Surface displacements between June and November 2011 are obvious.*

Maps showing displacements perpendicular to the main slope plane were also generated through DEM differences, projected on a plane parallel to the main slope plane. Displacements of more than 50 cm were observed for significant portions of the slope, and the movement of large (> 2 m diameter) individual rock blocks, possibly related to rockfall, also became evident, as can be seen in Figure 4.12.

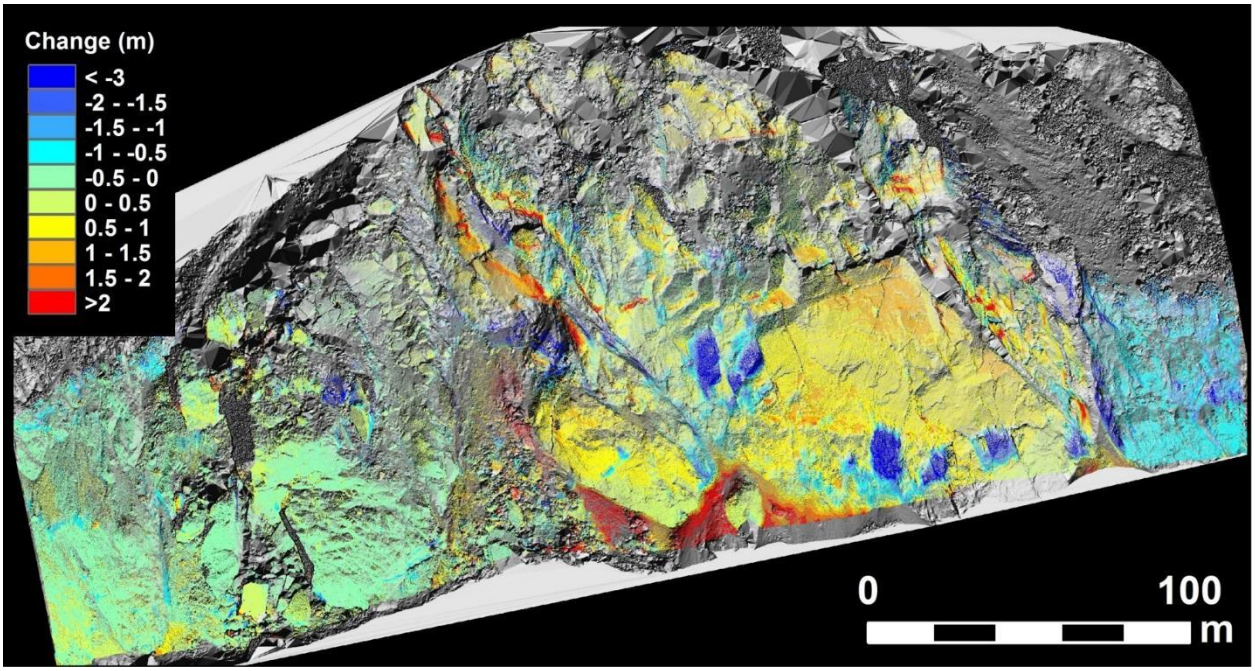


***Figure 4.12**: Surface changes perpendicular to the unstable rock slope at the Nevada test site, derived from LiDAR data. Large voids (blue patches) correspond to rockfall events, deposition areas (red triangular areas) correspond to depositional debris fans at the foot of the slopes, and relatively small displacements over broad areas (large yellow areas) correspond to actual slope displacements of large sliding blocks.*

### 4.3.5 Photogrammetry Results for the Nevada Test Site

Digital photogrammetric results for the Nevada test sites were used to generate high resolution DEMs and orthophotos (Figure 4.13), but problems with georeferencing and scaling of the models prevented us from getting high precision DEMs, making it impossible to measure small surface displacements. Photographs acquired from an aerial (UAV) platform were processed, in conjunction with rapid GPS (Trimble GeoExplorer GNSS) surveyed control points. Despite high surface point densities (> 1000 points per $m^2$), overall scaling differences on the order of 1 to 2 %, which amount to > 1 m errors over the > 100 m extent of the datasets, precluded us from confidently resolving surface displacements of less than the potential errors (i.e., displacements < 1 m). The low precision of the point clouds could be linked to the use of a quick GPS georeferencing for the control points, but other factors cannot be excluded. Digital photogrammetric processing was done using the Photoscan (Agisoft, 2016) software.

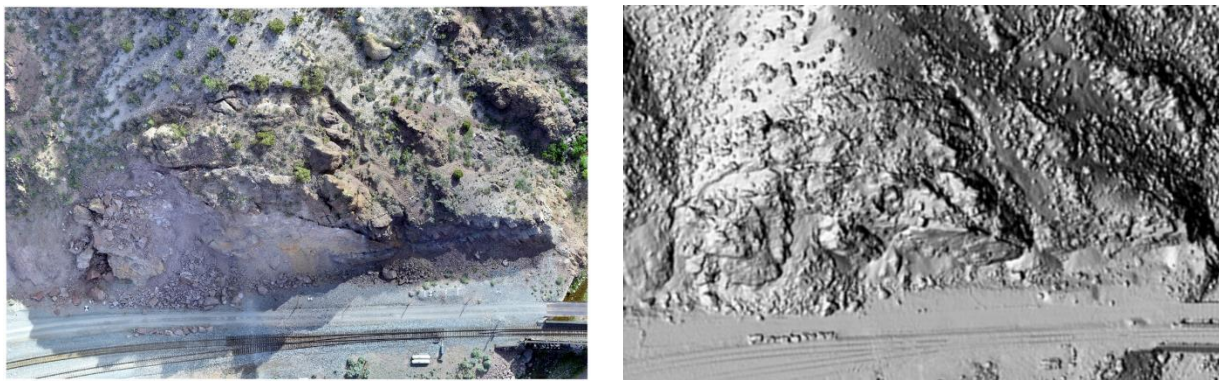

***Figure 4.13****: Orthophotographs (left) and corresponding hillshade map (right) derived from a high resolution DEM produced from digital photogrammetry at the Nevada test site.*

### 4.3.6 Photogrammetry Results for the M-10 Highway Site

Surface displacement measurements using digital photogrammetry gave very encouraging results for the M-10 highway retaining walls site, in Detroit, Michigan. Point clouds derived from the digital photogrammetry were collected in the spring and fall of 2014, had high surface point densities (> 1000 points per $m^2$), and were used to estimate surface displacements perpendicular to the retaining wall plane. Digital photogrammetric processing was done using the Photoscan (Agisoft, 2016) software.

Figure 4.14 shows a map of the surface displacement perpendicular to the wall plane between two data acquisition campaigns in March and June of 2014. Displacement measurements of individual points can be improved upon by considering larger sets of points and assuming rigid displacement of the wall sections, to reduce the noise associated with random variability of pixel positions. Figure 4.15 shows the distribution of residuals around the mean for both sections of the retaining wall shown in Figure 4.14, and it is clear that despite the presence of random noise, the distribution of residuals for both wall sections are clustered around distinctively different means. From this analysis it is possible to see that surface displacements as large as 2 cm took place between the adjacent wall sections.

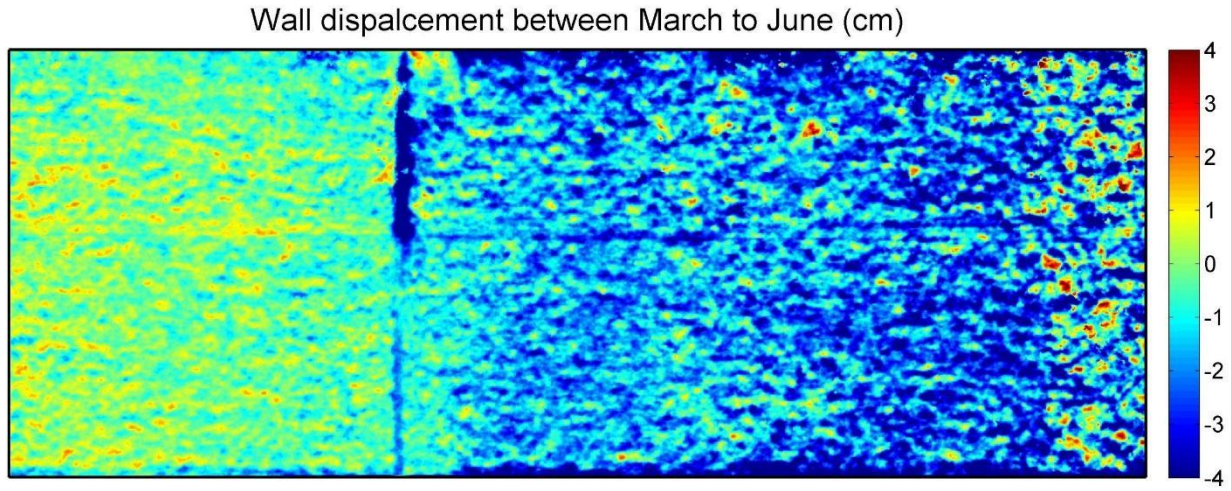


***Figure 4.14****: Displacement measured at retaining walls on the M-10 highway field site in Detroit, Michigan, between March and June 2014.*

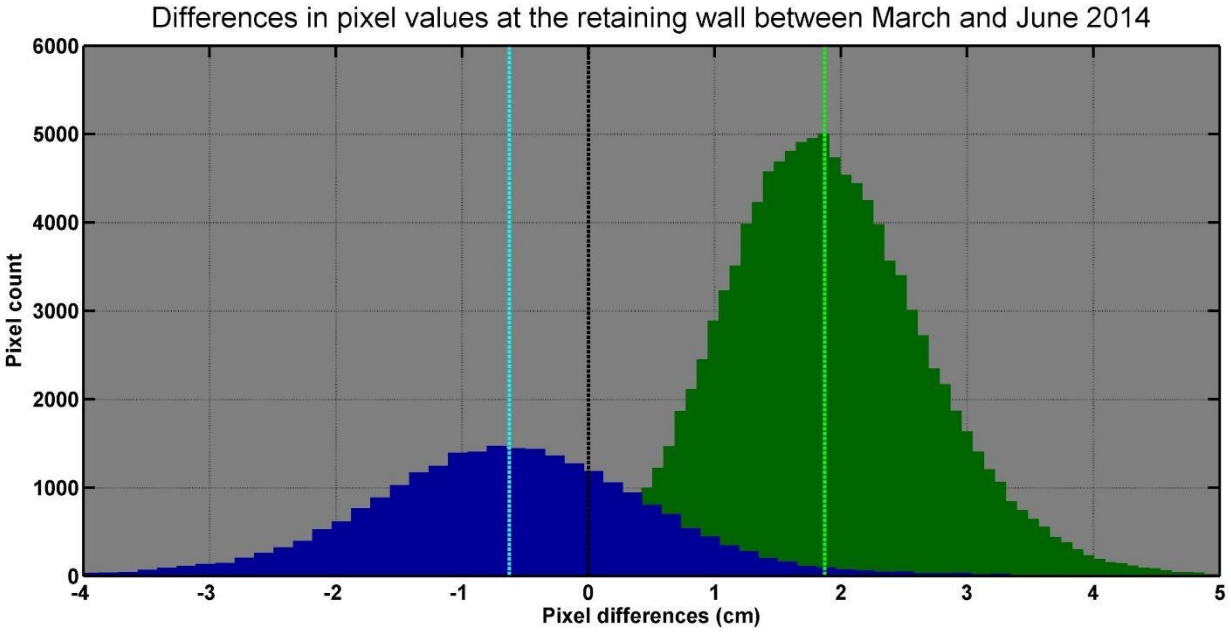


***Figure 4.15:*** *Displacement values for the pixels shown in Figure 4.14. Displacements for the left wall section are show by the blue histogram and displacement for the right wall section are shown in green. Light blue and green lines show the mean values for both displacement distributions.*

### 4.3.7 Photogrammetry Results for the Alaska Sites

Surface displacements measured for field test sites in Alaska gave mixed results. Extensive (> 1.6 km) sections of the Trans Alaska Pipeline were surveyed to produce high density (> 1000 points per $m^2$) point clouds, through digital photogrammetry methods. Surveys of the same pipeline corridor sections were done in the summer of 2014 and 2015, and the comparisons between both dates were used to estimate surface displacements. At the Lost Creek site, elevation differences obtained from subtracting DEMs gave vertical surface displacements in excess of 20 cm (see Figure 4.16). Digital photogrammetric processing was done using the Photoscan (Agisoft, 2016) software.

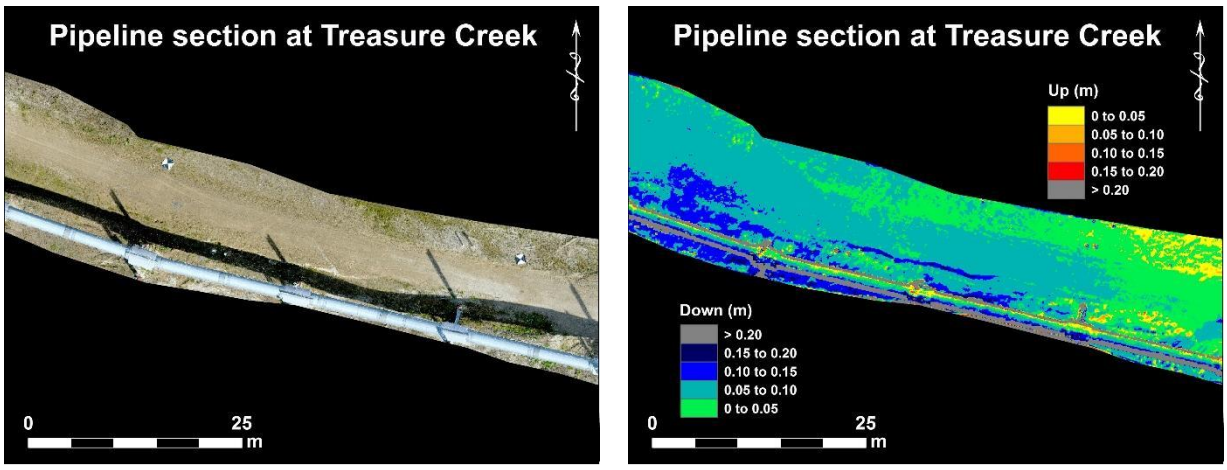


***Figure 4.16:*** *Orthophotograph (left) and vertical displacement map (right) for a section of the pipeline workpad at the Lost Creek site, derived from digital photogrammetry.*

Surface representations did not only cover the pipeline, but also the adjacent workpad, which allowed for comparisons between the pipeline and workpad displacements to be made. Figure 4.17 shows the vertical displacements experienced by the pipeline with respect the adjacent workpad, there clearly is some noise present, in part due to random surface changes happening on the workpad (e. g. erosion due to use and rain runoff), but a clear trend also emerges from the data. Such analysis can be used to check for the stability of the pipeline structure and problems related to vertical support member's foundations in permafrost environments.

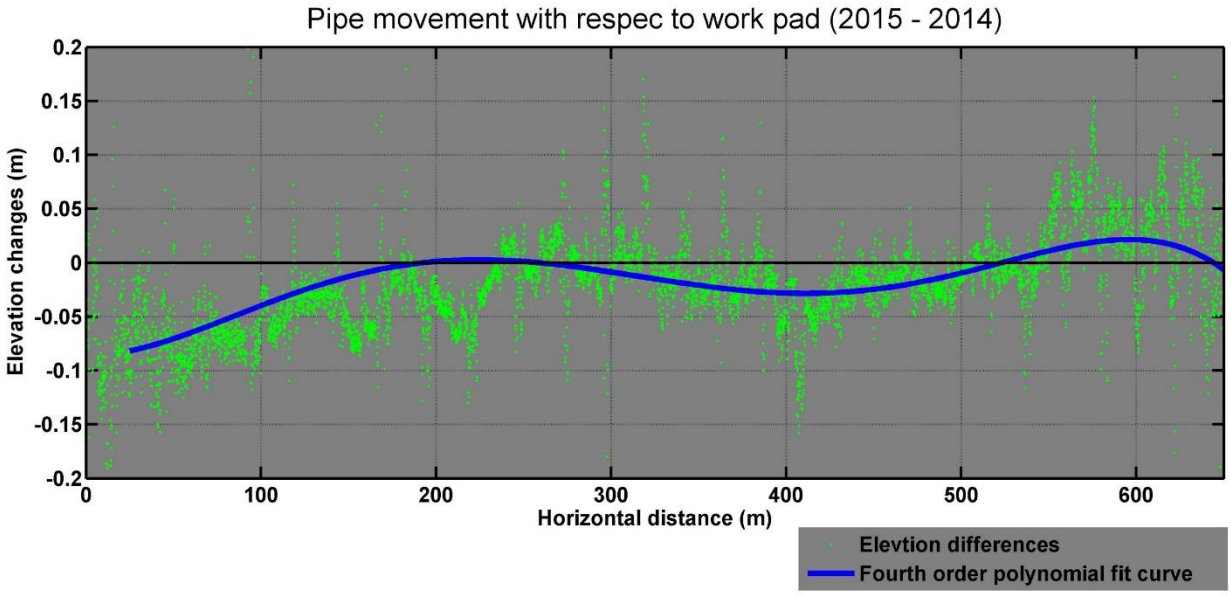


***Figure 4.17**: Vertical movement between the pipeline top and the adjacent workpad.*

### 4.3.8 Photogrammetry Results for the Laboratory-scaled Model Tests

Photogrammetry results for the scaled model laboratory test showed the capabilities of the method in a close range setting. Very high surface density point clouds (> 10,000 points per $m^2$) were generated from digital photogrammetry for the scaled model, with high precision ground control points, surveyed with a total station. Simulated displacements up to 12 cm were tested, with deformation patterns including rigid rotations and translations, but also non-rigid flexural deformation. Two digital photogrammetry software packages were tested and compared Photoscan (Agisoft, 2016), and Pix4D Mapper (Pix4D, 2016).

Displacement results of forward and lateral tilting (horizontal and vertical rotation) of the model retaining walls are seen in Figure 4.18, for both digital photogrammetry processing software outputs. Displacements exceeding 10 cm are easily resolved, the results from both software processing algorithms agree overall, and individual differences are small.

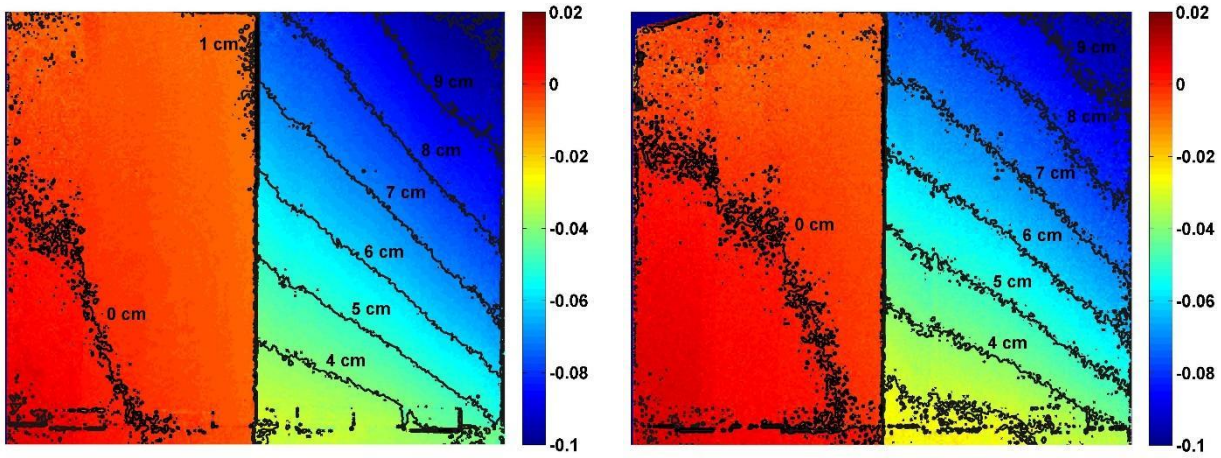


***Figure 4.18:*** *Displacement maps of the laboratory scaled model for retaining walls, corresponding to one of the wall displacement scenarios. The left panel show the results obtained with the Photoscan software, while the right panel shows the results obtained with the Pi4D software. Both software packages produce very similar results.*

Comparisons with high precision ground control point measurements show that displacement errors are relatively small, mostly within 1 or 2 cm (Figure 4.19).

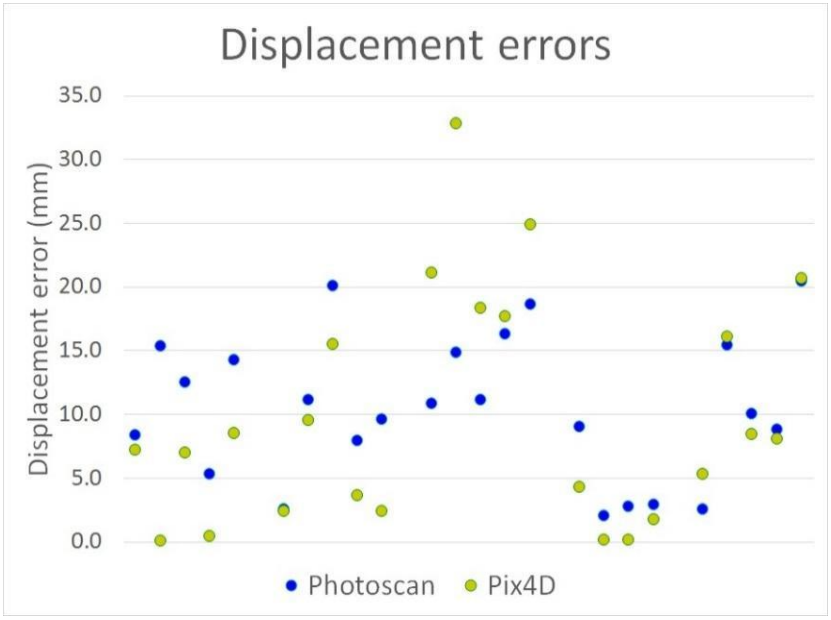


***Figure 4.19:*** *Displacements errors for 24 modeled retaining wall displacement scenarios.*

### 4.4. Comparison of Different Methods: Limitations and Challenges

Direct comparison of measured displacement obtained by the different methods was attempted when applicable, but in some cases such comparisons were not feasible. A comparison of satellite InSAR based displacement with displacement measurements obtain from other methods (e. g. LiDAR or digital photogrammetry) was not straightforward for any of the test sites where we collected data. Differences in time coverage, spatial resolution and data density, and direction of movement don't allow for a direct, quantitative comparison between surface displacements obtained from InSAR analysis vs. other methods. However, broad qualitative comparisons are possible, and in the case of the Nevada site, the areas showing the larges surface displacements derived from the InSAR analysis coincide with fieldwork inspection of the unstable rock slopes, as detailed in Bouali et al., 2016a, and Bouali et al., 2016b.

Comparisons between digital photogrammetry and LiDAR measurements of surface displacements are relatively straightforward. Both methods produce surface representations in the form of point clouds that can be compared in different ways, and from which similar surface displacement measures can be derived. In some cases the point clouds for common surface surveyed at the same time, were very similar, with relatively small differences that could be considered as part of the expected measurement errors. But in some cases the discrepancies between digital photogrammetry and LiDAR results were larger than what would be expected from random errors, and may be related with data acquisition problems, or other systematic error inducing causes. And in some cases, such large inconsistencies were also observed between digital photogrammetric datasets from different times, acquired over the same surface, as has been mentioned previously.

Figure 4.20 shows the comparison of a small section of the Nevada test site rock slope that was analyzed using digital photogrammetry and LiDAR methods. Data were acquired simultaneously, allowing to scale the photogrammetric point cloud to best match the LiDAR point cloud, and avoid the problem of scale mismatches previously mentioned for this site. Although the photogrammetric data seem slightly more noisy than the LiDAR data, the surfaces match each other within a few cm in most areas, and only differ by larger values in areas where the viewing geometry of either the LiDAR of the photogrammetry acquisition procedure (or both) was poor.

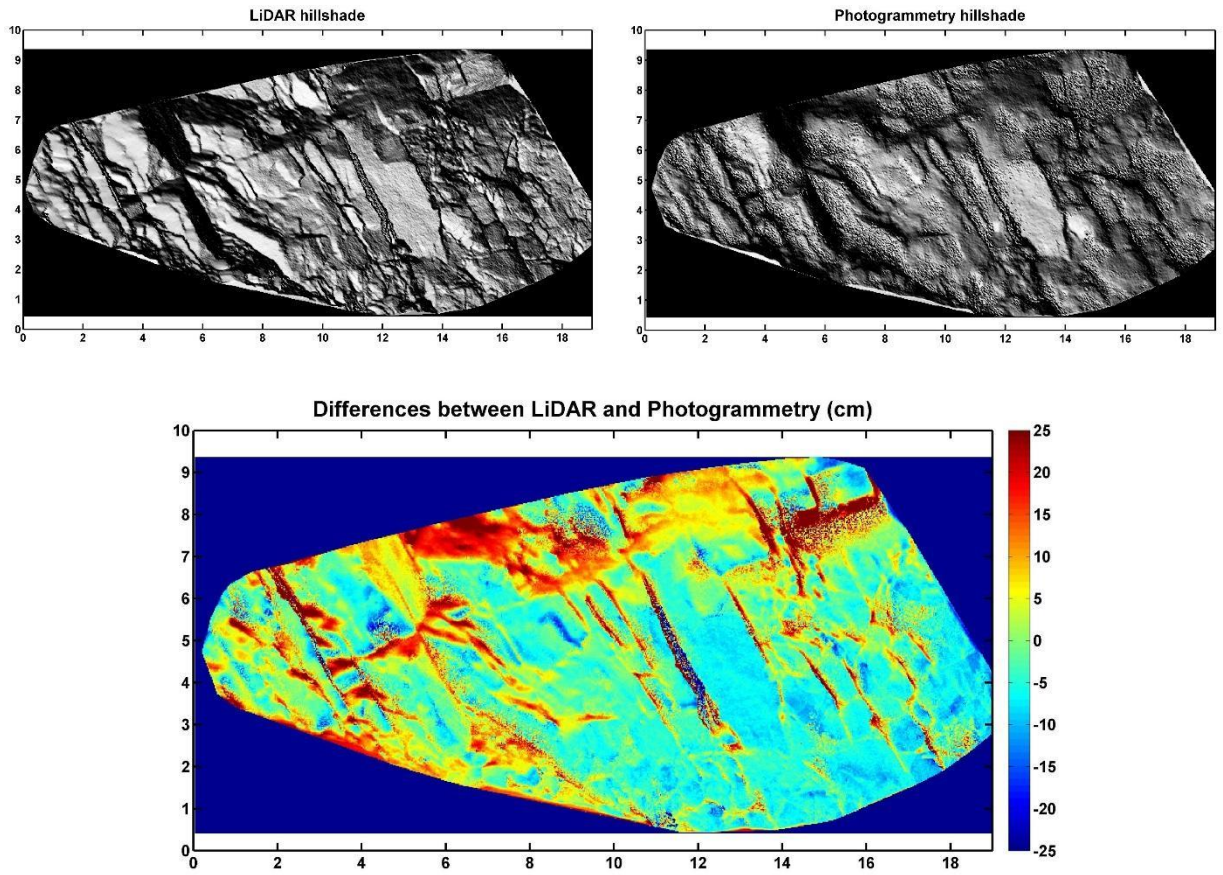


***Figure 4.20:*** *Surface representation results derived from digital photogrammetry and LiDAR. The upper left panel shows a hillshade map produced from a LiDAR point cloud, while the upper right panel shows the hillshade map of the same rock slope region produced from a digital photogrammetry point cloud. The lower panel shows the differences between the LiDAR and photogrammetry point clouds.*

Each method used has advantages, but also limitations and challenges. In case of the InSAR some of the main limitations encountered in this project include: low spatial resolution (≥ 7 m pixels), infrequent satellite passes (≥ 10 days), displacements in only one direction (the line of sight), data gaps in the presence of vegetation, inability to measure high deformation rates (> 4-5 cm/year, Crosetto et al., 2010), and a steep learning curve for the processing and interpretation of data.

General limitations of LiDAR have been extensively documented elsewhere (e.g. Shan and Toth, 2008), and the limitations of its application to landslides and slope instabilities have

also be documented by other authors (e.g. Derron and Jaboyedoff, 2010; and Jaboyedoff et al. 2012). Our datasets show similar error levels to those reported in the literature for LiDAR, and from our Nevada LiDAR datasets it is evident that displacements on the order of 10 cm can easily be resolved. The main limitations for the use of LiDAR include: the relative short distance that can be covered in a single scan (< 1 – 2 km), the difficulty of obtaining a complete coverage for complex or very rugged surfaces due to the scanning perspective, accumulation of errors when analyzing multi-scanned datasets, and a high cost of the hardware (i.e. the LiDAR instrument) needed for surveying.

Results from the digital photogrammetry show that in some cases the method may produce results with a quality comparable to LiDAR scanning, but some important limitations became evident from our fieldwork: a need for precise ground control points adds to the cost and resources that need to be invested in photogrammetric surveys. Adequate and stable lighting conditions are needed to obtain good results. Good optical contrast and structure are needed to produce acceptable results, although this is usually not an issue for natural surface.

### 4.5. Conclusions and Recommendations

A wide range of surface displacement measures can be captured with the different remote sensing methods tested in this project, applied to a variety of geotechnical assets. Strengths and weaknesses of each method have to be considered when deciding which processing strategy is most appropriate for each geotechnical asset monitoring case. Monitoring displacement of extensive asset corridors or networks that may show very small displacement rates (on the order of mm/year) may require the use of InSAR data, especially in areas with a high number of strong reflectors, like urban areas, or rocky, desert regions. For heavily vegetated areas, with steep and potentially quickly moving slopes, InSAR analysis may return poor results. InSAR stacking methods may offer the best alternative to obtain long term deformation time series, but point densities may be low (< 100 points per $km^2$).

For less extensive regions, in which the focus centers on particular assets, higher resolution methods like LiDAR and digital photogrammetry can be used to monitor displacements with high surface point densities. Point densities of larger than 1000 points per $m^2$ can be achieved with such methods, and surface displacements on the order of 1 – 2 cm can be resolved. LiDAR equipment and operation can be costly, and in many cases digital

photogrammetry can be applied to obtain comparable results, but digital photogrammetry methods usually require the simultaneous deployment of surveying methods to establish a precise and high quality control points network, which may add to the overall cost of such data collections. As digital photogrammetry methods evolved it may be possible that such additional control points network requirements could be relaxed, especially if high precision GPS location (e. g. RTK GPS) onboard of the surveying platform (e. g. UAV) or sensor (e. g. GPS integrated camera) reduce the camera location errors.

## Chapter 5: Performance Monitoring and Condition Assessment

### 5.1 Introduction

The objective of this chapter is to evaluate and demonstrate how remotely-measured displacement values can be used to rate the condition of geotechnical assets. Presented is a multi-tiered approach: a large-scale, low-resolution level in which critical areas are identified for further in-depth analysis which is performed at a local-scale, high-resolution level. Analysis of remote sensing data gives a diagnostic performance and condition assessment of the asset at each level, determining whether the asset needs immediate attention and further actions. If further actions are deemed necessary, they can be assigned to either the *further analysis group*, where data point to a potential hazard but additional examination is required, or the *explicit actions group*, where mitigation strategies must be devised because the asset has been deemed hazardous and may deteriorate or experience loss of performance (Schaefer et al. 2013).

The multi-tiered approach is then demonstrated on two case studies: (1) a slope stability analysis along a railroad corridor in southeastern Nevada and (2) a retaining wall along the metropolitan Detroit M-10 highway in Michigan. InSAR, LiDAR, and optical photogrammetry are the specific remote sensing techniques applied to these two case studies. Similar multi-tiered approaches can be easily adopted for any geotechnical asset along the transportation environment.

### 5.2 Performance Monitoring of Geotechnical Assets

Key steps in the geotechnical asset management (GAM) program are condition assessment and long-term performance monitoring (Sanford Bernhardt et al., 2003; Vessely, 2013). Several authors, including Sanford Bernhardt et al. (2003), Stanley (2011), Stanley & Pierson (2013), and Vessely (2013), have described the challenges of defining performance monitoring and condition assessment methods. For example, Stanley & Pierson (2013) discuss the minimal data available to aid in the understanding of geotechnical life-cycle performance under various conditions (e.g., during maintenance, under different external stresses, etc.). Geotechnical assets are expected to deteriorate. To mitigate complete failure – a disaster that could cause human casualties and loss of infrastructure and money – periodic repair and preventative maintenance would help reduce asset deterioration, thus extending the lifetime of

the geotechnical asset. Challenges arise when attempting to define specifics, such as the adequate level of maintenance required, where to apply maintenance, which assets to target first, and, surprisingly, what relevant variables to measure.

Ground movement and deformation is a key variable to measure in geotechnical asset performance monitoring. Ground deformation has traditionally been studied using in situ instrumentation, such as inclinometers, accelerometers, or continuous GPS monuments. Measurements of ground displacement and/or velocity, soil moisture, and groundwater pressure have all been correlated to slope failure (Mikkelsen, 1996). Installation and real-time monitoring of these variables was the only method towards determining the life-cycle position of a slope (or of the geotechnical assets built upon the slope) and, in turn, predicting the potential of a landslide. This method is reactionary and may work for slow-moving landslides, but cannot work for more rapid landslides where a negligible reaction time will not allow for mitigation (Zwissler et al. 2014; Smith et al. 2015). Therefore, proactive approaches using ground movement and deformation observations have been studied in order to hopefully predict the spatial and temporal extent of landslide occurrences.

A hypothesis created by Fukuzono (1985) and later studied by Voight (1989) stated there is a relationship between the strain applied to a material and the time of failure of that material. Figures 5.1 and 5.2 demonstrate two experimental scenarios where inclinometers measured the velocity of slope material during controlled landslides (Petley, 2004; Wartman & Malasavage, 2013). A linear inverse velocity vs time relationship has been observed in cases where brittle deformation, or failure along pre-existing planes of weakness, occurs (Kilburn & Petley, 2003; Petley, 2004; Wartman & Malasavage, 2013). Nonlinear inverse velocity vs time relationships have also been observed and have been interpreted as landslides exhibiting ductile failure mechanisms (Angeli et al., 1989; Petley et al., 2004; Petley & Petley, 2004; Federico et al., 2012; Wartman & Malasavage, 2013).

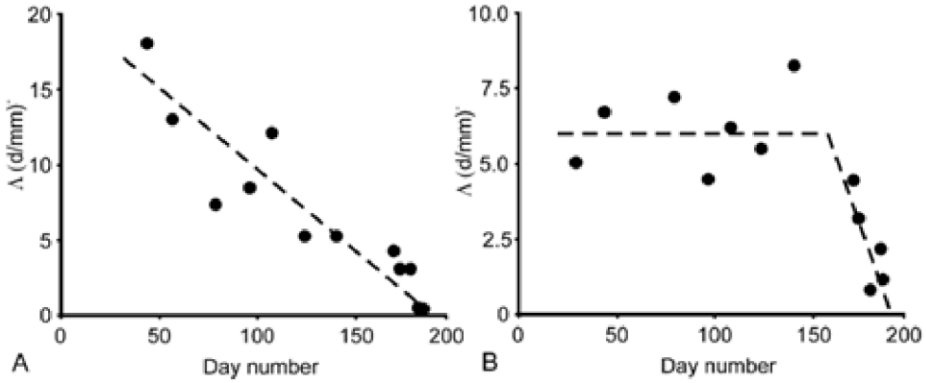


***Figure 5.1:*** *Inverse velocity plots of two inclinometers undergoing (A) linear acceleration with failure at day 180 and (B) steady-state creep until day 152 and sudden linear acceleration with failure at day 180 (Petley, 2004).*

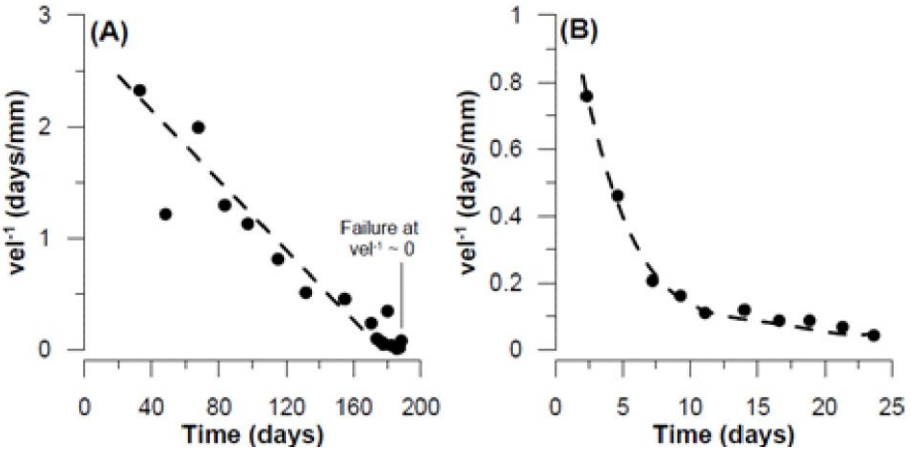


***Figure 5.2:*** *Inverse velocity plots of two inclinometers undergoing (A) brittle failure and (B) ductile failure (Wartman & Malasavage, 2013).*

Utilizing ground deformation to monitor performance and assess condition can be applied to a variety of geotechnical assets. Slopes along transportation corridors vary based on composition, deformation characteristics, and failure mechanisms. Slopes may be natural, artificial, or a combination of both. Surface deformation, observable via remote sensing techniques and not requiring subsurface data, may reflect the movement along a deep failure surface within the soil or rock mass of the slope. Deformation patterns can be matched with modeled deformation (Figure 5.3) to infer the deformation mechanisms and time of future potential landslides. Slope characteristics such as slope geometry, composition, and material

strength parameters play a major role in determining the stability and surface deformation patterns of a slope. Ideally, a measure of the deformation relative to the location of neighboring points (e.g., strain) should be considered when assessing the stability of slopes, but this task may be difficult with low resolution datasets. The evaluation of terrain deformation needs to be done within the context of that particular type of asset and the specific conditions under which it may fail while considering the external factors that play into slope deformation and stability.

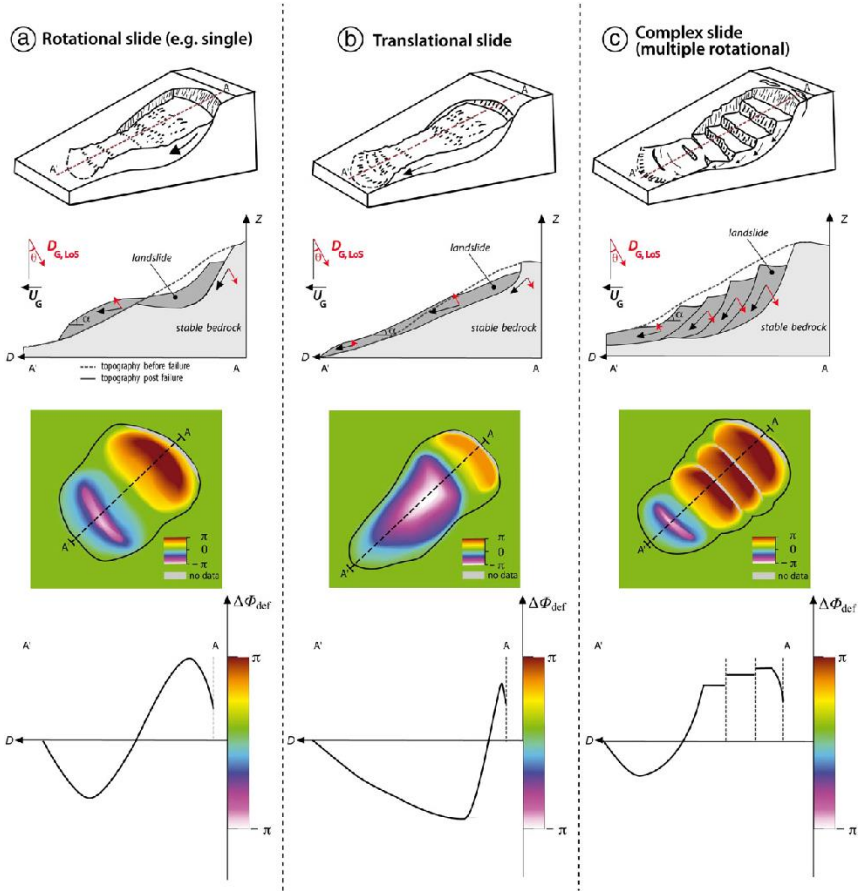


***Figure 5.3:*** *Surficial displacement pattern models illustrating how deep landslides may appear in processed InSAR results (Schlögel et al., 2015).*

Retaining walls also include a wide variety of designs. There are two main elements to consider when determining retaining wall performance monitoring techniques: the retaining wall itself and the backfill behind the retaining wall. Backfill stability may be approached similarly to slope stability problems, but the presence of the retaining wall will obviously provide support (per its function). Therefore, deformation monitoring may refer to data points on the retaining

wall or points on the backfill, depending on viewing geometry and capabilities of the remote sensing technique. Performance monitoring and condition assessment of the retaining wall infers information about the backfill and vice versa. The ideal situation is to acquire data on both elements. If deformation is measured on a large enough number of points along the retaining wall and the wall geometry is relatively simple, it is possible to model the wall as a rigid body, allowing for more precise displacement measurements.

### 5.3 Remote Sensing Techniques for Geotechnical Asset Performance Monitoring and Condition Assessment

Remote sensing techniques can be utilized for different steps incorporated into the GAM procedure. Terrain models, including digital elevation models (DEMs), can be generated using remote sensing. DEMs can then be used to characterize the surficial geometry adjacent to transportation corridors; slopes can be characterized and initially classified. High resolution imagery can also be used to rate slopes according to their stability and potential for failure or producing rockfalls that may affect the transportation corridor.

A variety of remote sensing techniques may be used to monitor geotechnical asset performance, including InSAR, LiDAR, and optical photogrammetry. Each of these methods have advantages and limitations that were previously discussed. All three techniques are capable of creating DEMs and measuring ground deformation. InSAR requires two images from different vantage points to create a DEM, and requires at least two images to measure ground deformation, with a larger number of images (>20) necessary to measure mm-scale ground deformations. LiDAR and optical photogrammetry require one acquisition to create a DEM and at least two acquisitions to measure ground deformation, with the optical photogrammetry requiring multiple images from various vantage points per acquisition. These techniques measure surface deformation, which, as described above, can imply deformation within the subsurface.

### 5.4 The Multi-tiered Approach

Remote sensing techniques can be used to apply a multi-tiered approach towards performance monitoring and condition assessment for GAM (Figure 5.4). For example, a large-scale level analysis (with respect to deformation measurements) could be the identification of all slopes along a transportation corridor that show any magnitude of deformation. Slopes that are

identified as potentially unstable through this approach can then be further examined with targeted LiDAR and optical photogrammetry data acquisitions. The combination of all three techniques allows for a robust identification of potential hazard regions along the transportation corridor, as shown with the two case studies below.

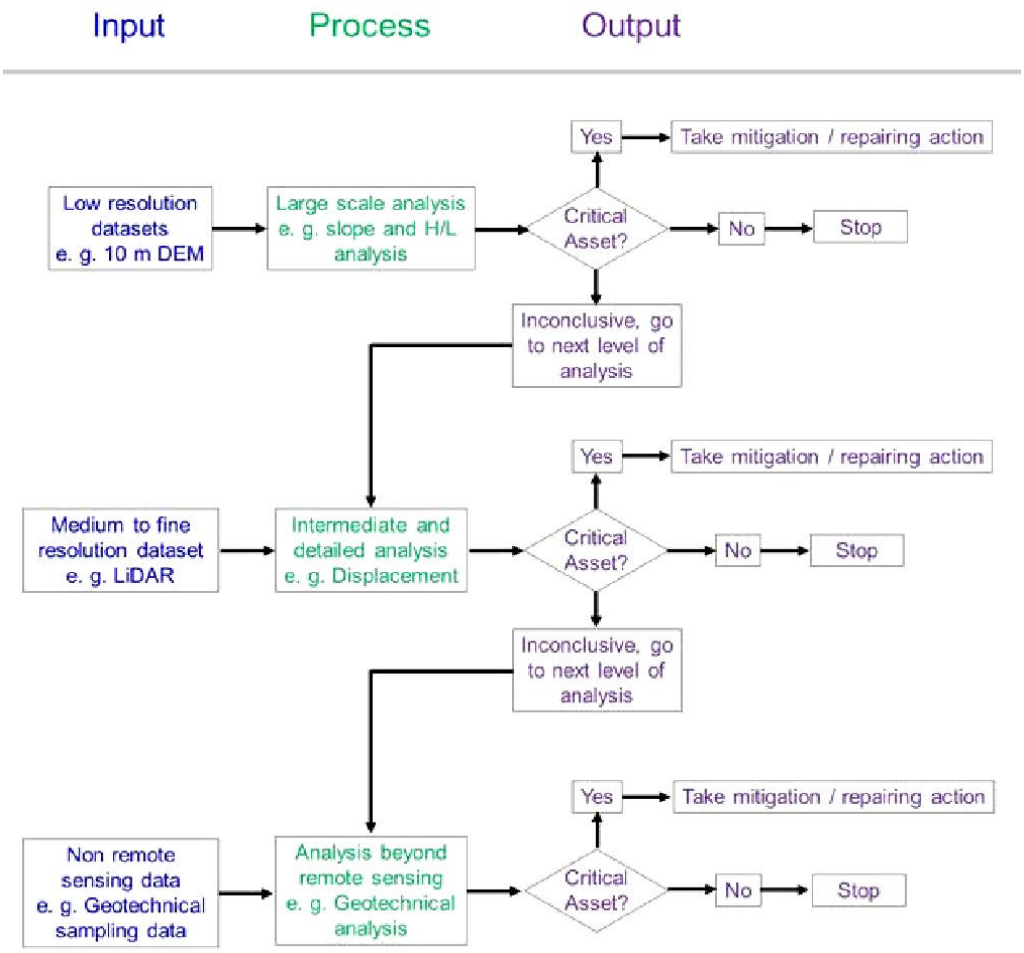


***Figure 5.4:*** *Flow diagram illustrating the multi-tiered analysis process proposed for monitoring geotechnical assets.*

### 5.5 Case Study I: Unstable Slopes along Railroad Corridor in Southeastern Nevada

The Nevada study site is a railroad transportation corridor that follows the low valley topography of a canyon system. Slopes of varying degrees of steepness (e.g., near-vertical to gently dipping) are located along one or both sides of the route along many segments of the tracks. Most of the slopes are composed of volcanic rock, such as rhyolite and tuff, as well as

metamorphosed welded tuff-breccia with basalt-capped plateaus upon the tallest slopes (Schaefer et al. 2015; Bouali et al. 2016).

The railroad corridor in southeastern Nevada (Figure 5.5) is a study site that illustrates the benefits of applying the large-scale level analysis. Utilizing a GIS shapefile of the railroad track segment of interest, the first step of the analysis was to examine the corridor and determine what slopes may be proximal enough to the tracks. A 1-km buffer area on each side of the tracks was defined (Figure 5.6A). Then, using a 10-m digital elevation model (DEM) from the National Elevation Dataset (NED), slopes located within the buffer area with a slope angle greater than 30° were identified as potentially unstable (Figure 5.6B). These slopes are potential source areas for landslides that may affect the railroad corridor. The next step was to calculate the height-to-length ratio (H/L) of each slope within the buffer area. An H/L threshold of 0.25 (a somewhat conservative value) was used; H/L = 0.25 correlates to large landslides (105 to 106 $m^3$) according to global H/L catalogs (Hunter & Fell, 2002). Figure 5.6C shows the number of potential landslide source locations each pixel is exposed to, with a maximum of 6,677 sources at some locations. The final step was to incorporate ground displacement rate (velocity) data from remote sensing techniques. For this study site, the only remote sensing technique available at the large, regional scale was satellite-based InSAR. PSI velocity calculations for the segment of railroad corridor is shown in Figure 5.6D. End results of this analysis can be displayed as relative exposure map (Figure 5.6E), which spatially presents 95 and 99 percentile of relative exposure for the railroad corridor, while Figure 5.6F displays the combined information from the exposure map and from ground deformation derived from InSAR


***Figure 5.5:*** *29-km segment (orange) of the railroad corridor study site in southeastern Nevada.*

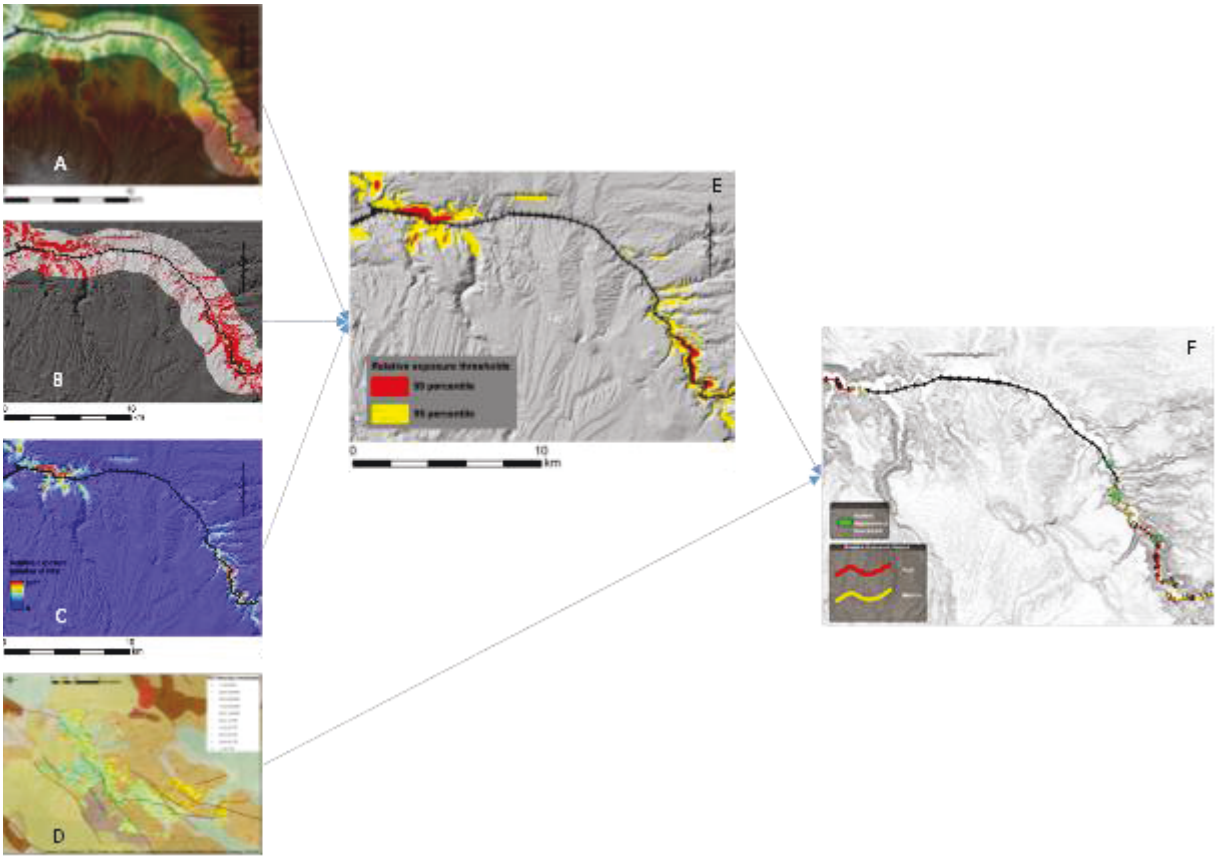


***Figure 5.6:*** *(A) 1-km buffer zone; (B) areas with slope angle > 30°; (C) potential landslide locations due to number of source areas per pixel; (D) InSAR ground displacement rate; (E) exposure map based on (A), (B), and (C); (F) hazard zones along railroad corridor based on (D) and (E).*

## 5.6 Case Study II: Retaining Wall on M-10 Highway in Metropolitan Detroit, Michigan

The retaining walls on the M-10 highway in metropolitan Detroit (Figure 5.7) offered a favorable study location for detailed-scale analysis. This portion of the M-10 retaining wall was experiencing rotational displacement (top end towards the highway) and so high resolution optical photogrammetric imagery were collected. Point clouds generated from these imagery were used to interpolate raster surfaces parallel to the actual wall surface with pixel values of the distance between the optical camera and the retaining wall. Raster surfaces created from imagery obtained at two different acquisition dates (Spring 2014 and Summer 2014) were differenced to create a map that shows the relative displacement of the retaining wall between the acquisitions (Figure 5.6). Light green colors represent zero displacement. Blue colors represent displacement away from the camera and highway (into the page). Red colors represent displacement towards the camera and highway (out of the page). Displacement magnitudes range from ±4 cm. Displacement distributions for two segments of the retaining wall are shown in Figure 5.7, where the green displacement distribution plot corresponds to the retaining wall between joints 3 and 4 and the blue displacement distribution plot corresponds to the retaining wall right of joint 4 (Figures 5.7 & 5.8). Figure 5.8 illustrates the displacement near two retaining wall joints and aerial-view interpretations of wall movement. These results can then be used to infer possible failure mechanisms and the need to mitigate a potential future wall failure at these problem locations along the M-10 highway, if necessary.


***Figure 5.7:*** *Retaining walls and joint sets along the M-10 highway in metropolitan Detroit.*

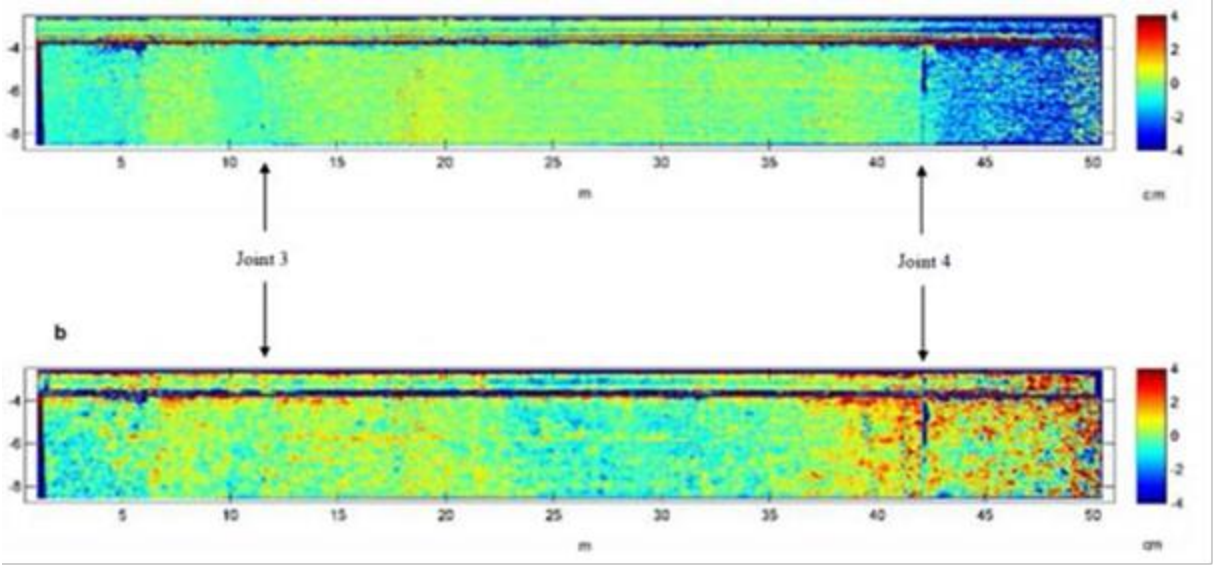


***Figure 5.8:*** *Displacement map along the retaining walls (Figure 5.7). Displacement is measured in cm in a direction towards/away from the road (in and out of the page, respectively).*

## 5.7 Conclusion

Geotechnical assets are sometimes ignored or not included in the transportation asset management system concept. Reasons for this may include the difficulty of establishing long-term expectations on the asset's performance and life-cycle behavior or that monitoring the health of a geotechnical asset may require expensive and time-consuming methodologies. Monitoring the surface displacement or deformation of geotechnical assets, however, can be a highly valuable approach for GAM purposes. Surface deformation can be used to infer an asset's internal/subsurface condition. Traditional field methods to measure ground deformation may be an expensive and resource-intensive approach towards monitoring the state of geotechnical assets. This project proposes the use of remote sensing methods (InSAR, LiDAR, and optical photogrammetry) to identify and measure surface displacements across various geotechnical assets.

# Chapter 6: Geotechnical Asset Management Decision Support System

## 6.1 Introduction

A Geotechnical asset management decision support system (GAMDSS) can be defined as a web friendly application that can be used to share information on GAM with users and facilitate its analysis. Open source, free software is used to build the GAMDSS, which includes the client and server software. The GAMDSS is designed to host a series of information layers that can be managed remotely, allowing the user to upload and manage information, in the form of layers and projects. Data types that can be managed include high resolution raster images using Web Mapping Services (WMS), vector data types based on Google's KML data format, vector feature info popups, and information displayed as legends for the raster and vector data layers. The server software runs on Linux via an Apache webserver, while the client web application is compatible with most common web browser software, allowing in cases where there is internet connectivity, to use the application remotely in the field.

## 6.2 Server Software

A software suit, including Apache, PostgreSQL, Django, and GeoServer, are used for the GAMDSS server, all of which are open source and widely used in the web community. This software receives web requests, processes the data, and returns a response. Apache is world's most used web server. PostgreSQL is an object-relational database management system. Django is a Python based web framework. Django is used as a link between Apache and PostgreSQL, receiving web requests from Apache and interacting with the dataset queries via PostgreSQL. The management of the GAMDSS database content is also possible through Django, allowing users to manage projects remotely, uploading new layers or creating new projects. Figure 6.1 shows a screen capture of the Django administration interface.

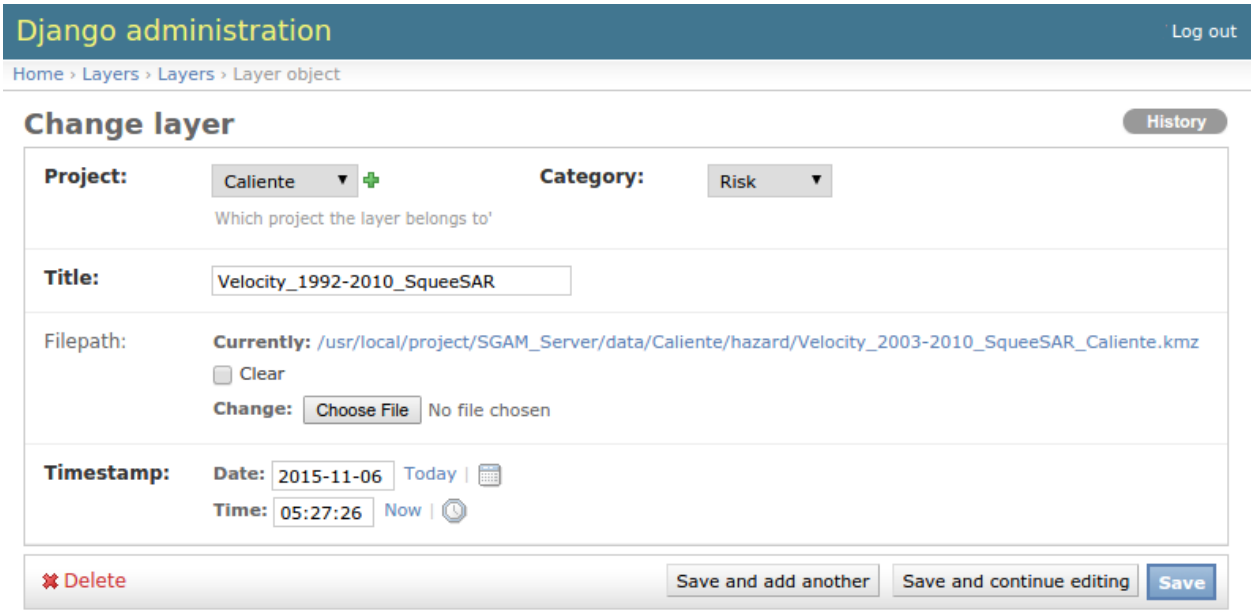


***Figure 6.1:*** *Screen capture of the server administration page.*

An open source Web Mapping Service (WMS) called GeoServer is used in the GAMDSS to access high resolution raster imagery. The efficiency of raster datasets display depend on the generation, storage and display of overviews, which are reduced resolution versions of the original raster image, and on a process called tiling, which segments images in smaller subsets that can be transferred over the internet, instead of sending the whole original image. Tiles produced from the tiling algorithm are compressed JPG images, which also reduces the amount of information stored and transmitted, as compared to the original high resolution images. Combining the overviews and tiling operation allows for greater efficiency in GeoServer processing, as the lowest appropriate resolution overview is chosen for on-screen display. This allows for high resolution to be used in the database, but requires its full resolution display only for cases of very close-up viewing of the imagery.

### 6.3 Client Software

A combination of HTML, JavaScript and Sencha ExtJS 4.2.1., was used to build the GAMDSS client web application. HTML and JavaScript are languages commonly used for web applications, and ExtJS is a JavaScript application framework used by the GAMDSS to build the Graphical User Interface (GUI) as well as the communication with the server software.

Several JavaScript libraries are also included in the client application, to provide geospatial mapping functionality. Google Maps API V3 is used for generic mapping functionality which the remaining client functionality is built from. GeoXML3, an open source KML parsing library, enables the client application to read and display KML files. KML files, another google standard, can incorporate both raster and vector components such as point features, line features, polygon features, and ground overlays. Since GeoXML3 is open source, it was modified to provide additional functionality to support the display of custom legend overlays using ExtJS, enabling content creators greater flexibility when determining how to present information in the GAMDSS.

### 6.4 User Interface

A user interface for the GAMDSS displaying a map view of the datasets allows to handle the data and visualize different layers of information. A control panel on the right side of the interface has the dropdown menu from which different projects or study area can be selected for viewing. Once a project or study area has been chosen, a series of other data layers can be selected for that specific project or site, including Hazard, Site Variable, and Ancillary datasets. Layers can be added and displayed individually or in combinations, as both raster or vector datasets.

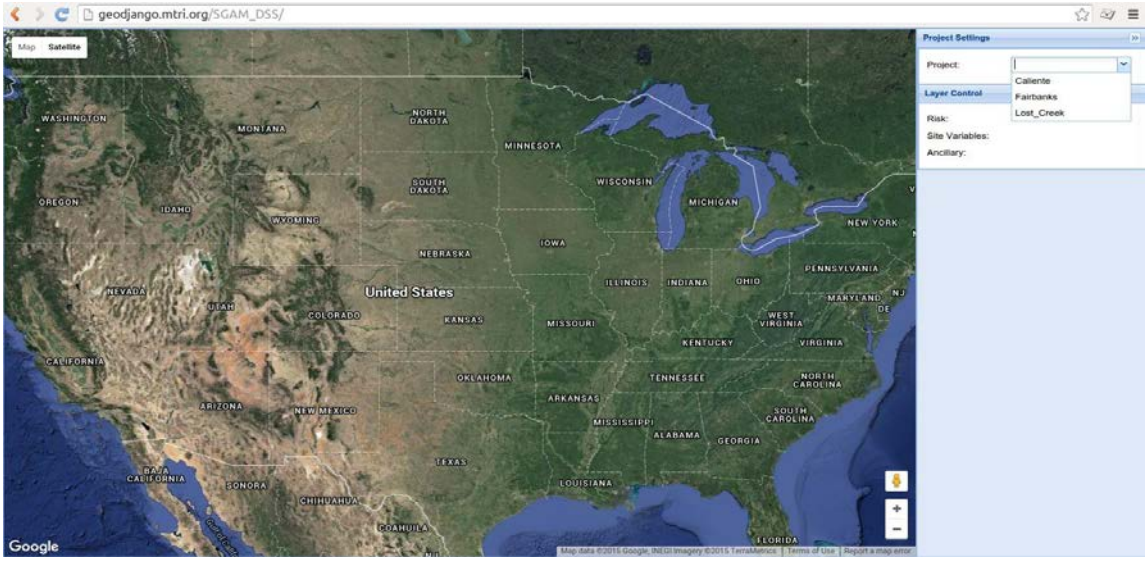


***Figure 6.2:*** *Screen capture of the GAMDSS graphic user interface.*

Legends and tags can also be displayed, depending on the zooming level of the respective layer. Legends can be rearrange or minimized by the user, to create a more personalized and convenient display. Depending on the nature of the datasets, zooming levels can display very high resolution datasets, for instance, orthophotographs generated from digital photogrammetry with a pixel size of 2 cm can be displayed at full resolution in the GAMDSS, which is a much higher resolution than what would be allowed through Google Maps. At very high zoom levels the map background will switch from the standard satellite imagery displayed in Google Maps, to whatever raster layer is loaded at the time in the GAMDSS (see example in figure 6.3).


***Figure 6.3:*** *Screenshot of GAMDSS user interface at a very high zoom level.*

## 6.5 Nevada Case Study

The GAMDSS was applied to the Alaska and Nevada field test sites, and here we present the Nevada case study. For this example we consider the 30 kilometer railroad corridor previously described in this report, which is subject to rockfall, slope instability, and related problems. The GAMDSS allows three layers of data to be displayed: hazards, site variables, and ancillary. Hazard layers include products of the performance and condition assessment analysis discussed in Chapter 5, which take some of the input displayed through the site variables layers, like slope, etc. The ancillary layers provide extra information on the context of the problem, and

it includes layers like the geology, etc. Figure 6.4 shows the terrain slope (in degrees) of the Nevada test site, as a raster layer, over a high resolution satellite imagery background, i.e. the standard Google Maps high resolution satellite imagery background.

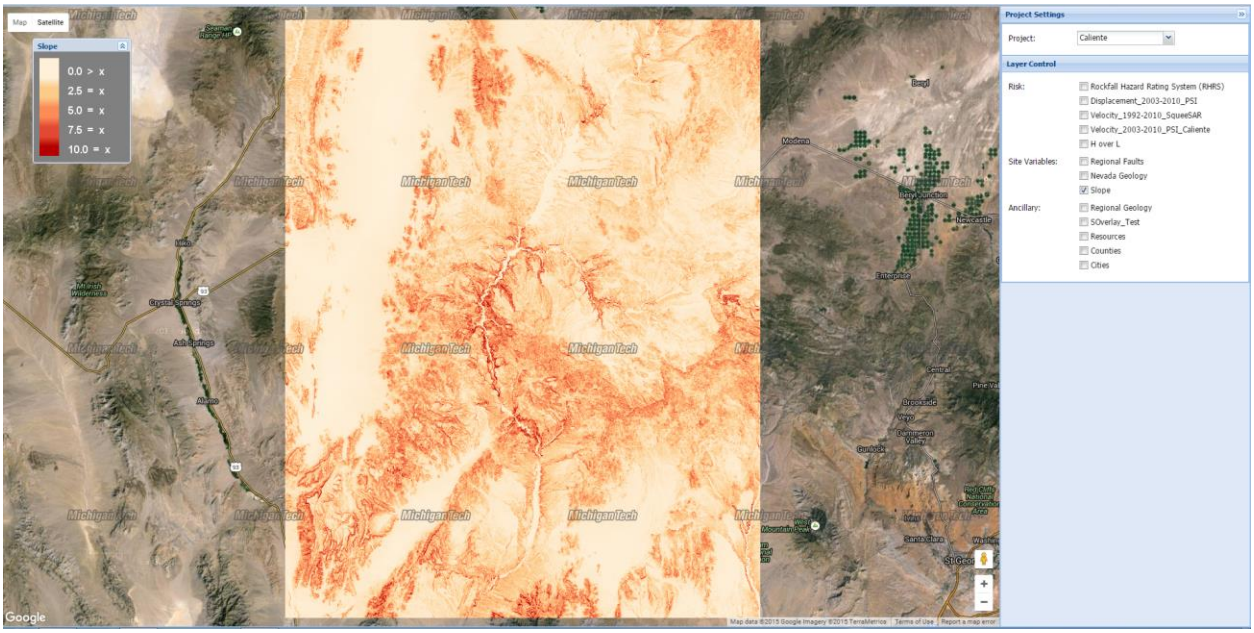


***Figure 6.4:*** *Slope map of the Nevada test site.*

Figure 6.5 shows the geology layer contained in the ancillary layer dataset. Information on the geological units from this layer can be displayed by clicking on the map units. Other information that can be displayed for the geology layer includes the area, perimeter, USGS standard nomenclature, etc. Similar capabilities would apply to other ancillary data layers (e.g. faults, etc.).

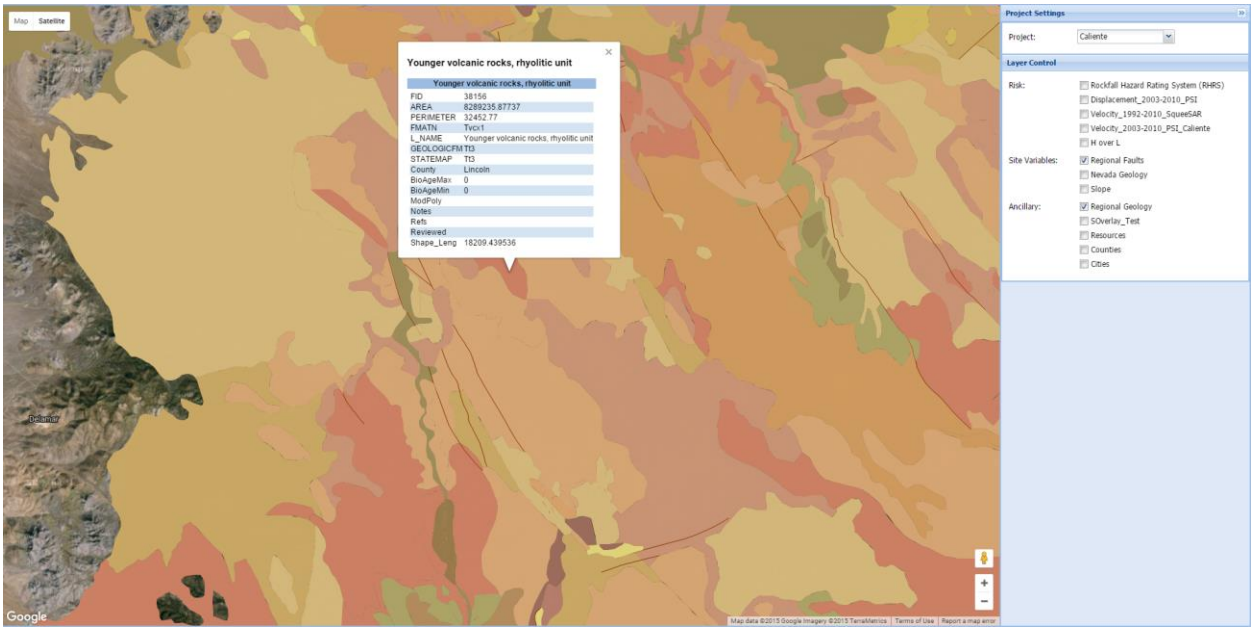


***Figure 6.5:*** *Screen capture of the geology and regional faults layers displayed in the GAMDSS.*

The hazard category contains layers that are related to slope performance and long term stability. Figure 6.6 shows the surface velocity derived from InSAR data, for the Nevada test site. InSAR analysis was based on European Space Agency (ENVISAT satellite) radar images, as described in Chapter 4. The displayed points correspond to individual pixels, with colors corresponding to the magnitude of the displacement velocity (red is downward and flue is upward) within ± 20 mm/year. Many different information fields can be associated to each layer and with each element in a layer, in this case, with each point where velocity has been measured, including the average velocity value, the total displacement, individual displacement between successive InSAR images, etc.

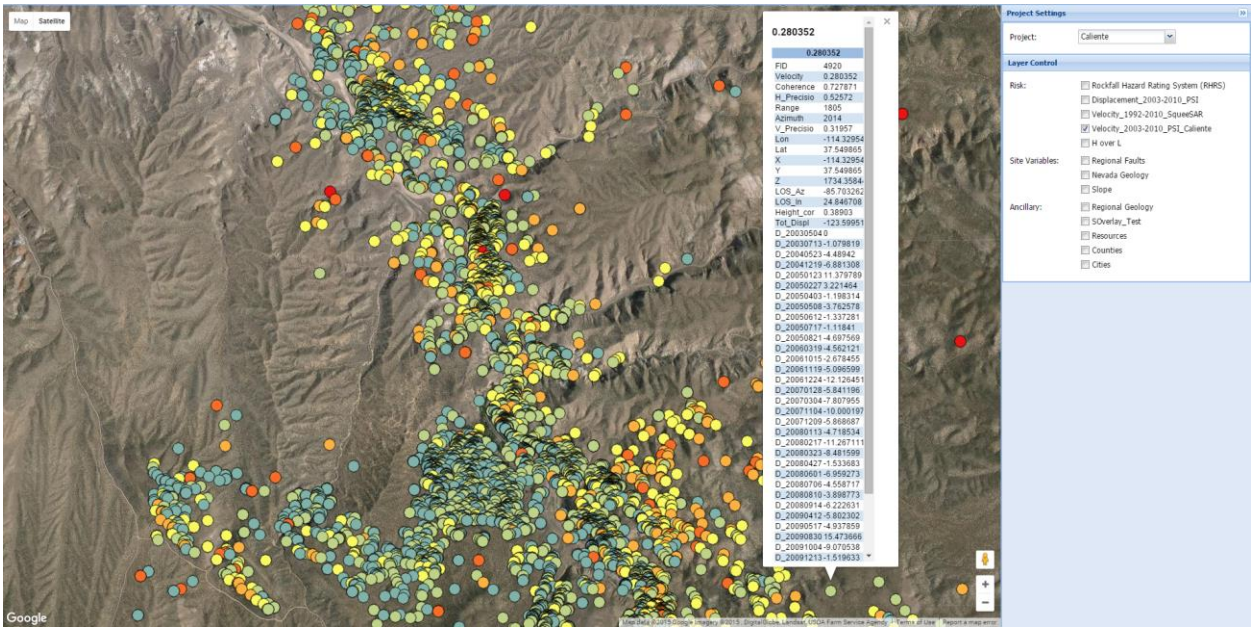


***Figure 6.6:*** *Ground velocity (mm/year) data displayed across the Nevada study area.*

## 6.6 Conclusion

Decision support systems applied to geotechnical asset management can be a useful tool for visualizing and analyzing data in a geographic information system environment. The GAMDSS provides a solution that incorporates hazards, site characteristics and ancillary information provided by the user, in a single web based platform. The GAMDSS uses open software tools, it is designed to be user friendly, and easily accessible from most web platforms. High resolution raster dataset can be displayed in the GAMDSS through GeoServer, while vector data in .kml format can also be added as data layers. The study case for the Nevada test site presented in this chapter show how the GAMDSS can be used to display information that is useful for asset management purposes.

# Chapter 7: Cost-benefit Analysis of Remote Sensing Methods Applied to Geotechnical Asset Management

## 7.1 Estimating Costs of Different Technologies and Platforms

Two scenarios are considered for estimating costs, an "in-house" built capacity and an outsourcing scenarios. In the "in-house" scenario the physical resources and knowledge necessary to apply the method are acquired or developed within the transportation agency or transportation system administrator. Costs associated with the "in-house" scenario include the initial investment in equipment, analysts and operators training, and long term cost of operation. In the outsourcing scenario the different services are hired or contracted to a company or commercial provider, to obtain a final product, e.g. point clouds or other surface representations from a LiDAR or digital photogrammetry survey. To compare both types of scenarios, costs will be annualized when possible, and initial investment cost will be distributed over a period of time estimated to be equivalent to the useful time for the equipment or technology.

The estimation of whether the "in-house" or the outsourcing scenarios are a better choice for an agency depends on many factors, including the scale of the agency's budget, the volume of work that would be routinely done using the technology under consideration, and other factors. Large budget and extensive work volumes may require developing "in-house" capabilities, which may be more costly initially (e.g. due to initial investment), but could pay off on the long run, as the initial investment is recovered, and subsequent availability of in-house capabilities results in cost savings. Smaller budgets and relatively low work volume cases may be more efficiently dealt with through outsourcing. The choice between the "in-house" vs. the outsourcing options may also depend on whether a technology in questions is available in both or only one forms.

## 7.2 Satellite-based InSAR Costs

Costs for development of "in-house" InSAR analysis capabilities include initial investment costs of buying software and hardware, and developing the knowhow, i.e. technical training of personnel. Sustained operation costs include computer time and related costs (data storage, etc.), as well as the operators and analyst salaries. Data acquisition costs depend on the type of radar images used, but can also be substantial if stacking methods requiring tens of

images to be used. For the purpose of cost comparisons, a standard work volume scenario is considered, and the costs of the data analysis for both "in-house" and outsourcing will be referred to such scenario. The scenario considers between 1 and 10 locations being analyzed, over a corridor length between 100 and 1000 miles. Table 7.1 shows the costs of different types of radar satellite images, and the time periods they cover, as well as revisit period and ground resolution.

***Table 7.1:*** *InSAR satellite images characteristics.*

| Satellite | Mission Timespan | Revisit Period (days) | Ground Resolution (meters) | Price Per Image (US Dollars)** |
|---|---|---|---|---|
| ERS-1 | 1991 - 2000 | 35 | 25 | $212 - $354 |
| ERS-2 | 1995 - 2011 | 35 | 25 | $212 - $354 |
| RADARSAT-1 | 1995 - 2013 | 24 | 10-100 | $3,047 - $3809 |
| ENVISAT | 2002 - 2013 | 35 | 25-150 | $354 - $591 |
| ALOS PALSAR | 2006 - 2011 | 46 | 7-100 | $42 - $709 |
| RADARSAT-2 | 2007 - | 24 | 3-100 | $3,047 - $7,110 |
| COSMO-SkyMed | 2007 - | 16 | 1-100 | $680 - $2,268 |
| TerraSAR-X | 2007 - | 11 | 1-16 | $875 - $7,972 |
| Meteor-3M | 2009 - | 3 | 400-1,000 | $30/$40 - ? |
| ALOS PALSAR-2 | 2014 - | 14 | 1-100 | $1,257 - $4,191 |
| Sentinel-1A | 2014 - | 12 | 4-80 | Free of cost |
| SEOSAR/Paz | 2015 - | 11 | 1-15 | Will be publically available |
| Sentinal-1B | 2016 - | 6 | 4-80 | Will be publically available |
| COSMO-SkyMed 2nd Generation | 2016 - | 1.5-10 | 1-35 | Will be publically available |

**US Dollar exchange rates (January 2015). NA = not available for commercial or educational use. Prices and data availability listed for users in the United States.

Table 7.2 summarizes the expected "in-house" costs for an initial investment in hardware and software, and the long term operational cost associated with labor and data storage, as well as radar images cost. Table 7.3 summarizes our estimation of outsourcing costs for the InSAR analysis.

***Table 7.2:*** *Summary of costs for in-house InSAR analysis capacities*

| **Item** | **Cost Estimate** | |
|---|---|---|
| | **Low** | **High** |
| Computer hardware | 1,500 | 2,500 |
| Software | 8,000 | 65,000 |
| Annual data storage | 4,000 | 4,000 |
| Annual analyst labor | 3,200 | 16,000 |
| InSAR images | 20,000 | 200,000 |
| **Total** | **36,700** | **287,500** |

***Table 7.3:*** *Summary of costs for outsourcing the InSAR analysis*

| **Item** | **Cost Estimate** | |
|---|---|---|
| | **Low** | **High** |
| Outsourcing InSAR analysis | 20,000 | 250,000 |
| **Total** | **20,000** | **250,000** |

**7.3 LiDAR Costs**

LiDAR costs are strongly related to the platform from which the data are acquired. Aerial LiDAR costs can be very high because of the aerial platform, and the high power laser involved in the scanning. Costs presented by Vincent and Ecker (2010) for aerial LiDAR ran as high as $8,321 per mile of corridor (see also discussion of this case in Chang et al. 2014). Table 7.4 summarizes the costs for the "in-house" LiDAR case using a standard work volume scenario.

***Table 7.4:*** *Summary of costs for in-house capacities for aerial LiDAR analysis*

| **Item** | **Cost Estimate** | |
|---|---|---|
| | **Low** | **High** |
| Total (non-itemized) cost | 25,200 | 541,000 |
| **Total** | **25,200** | **541,000** |

For practical purposes most agencies are likely to outsource aerial LiDAR work. The outsourcing costs depend on the work load and the type of products that are required, a study by the USGS National Data Elevation Assessment reported costs ranging from $90 to $ 21 per square mile, for large areas surveyed (> 5000 sq. mi) in 2012, while the State of Michigan

reported costs between $100 and $250 per square mile, for similarly large surveys in 2013 (State Of Michigan Center For Shared Solutions, 2013). Slightly higher costs of $335 were reported for Wisconsin in 2014 (McDougal, 2014), and $344 per mile estimated for Vermont in 2015 (Vermont Center for Geographic Information, 2015). This gives us an idea of the likely range of prices that could be encountered in the market. Applied to our standard work scenario, the estimated costs are presented in Table 7.5.

***Table 7.5:*** *Summary of costs for outsourcing the aerial LiDAR analysis service*

| **Item** | **Cost Estimate** | |
|---|---|---|
| | **Low** | **High** |
| Outsourcing LiDAR analysis | 25,000 | 521,00 |
| Annual data storage | 200 | 20,000 |
| **Total** | **25,200** | **541,000** |

Mobile LiDAR costs have been documented by Vincent and Ecker (2010), Yen et al. (2011 and 2014), and Chang et al. (2014), including initial investment and long term operation costs. As with previous cases the costs depend on the types of data being collected and the expected final products being delivered to the client. Table 7.6 summarizes our "in-house" estimate of mobile LiDAR costs.

***Table 7.6:*** *Summary of costs for in-house mobile LiDAR expertise*

| **Item** | **Cost Estimate** | |
|---|---|---|
| | **Low** | **High** |
| LiDAR instrument | 5,000 | 200,000 |
| Analysis software | 500 | 80,000 |
| Computer hardware | 1,500 | 2,500 |
| Annual data storage | 60 | 600 |
| Ground control surveying (rapid)[1] | 38,500 | 531,000 |
| Ground control surveying (high accuracy)[1] | 993,300 | 9,933,000 |
| Data processing labor | 24,000 | 240,000 |
| **Total (with rapid control)[1]** | **69,560** | **1,054,100** |
| **Total (with high accuracy control)[1]** | **1,024,360** | **10,456,100** |

[1]Two sub-scenarios are considered here, depending on whether rapid or high accuracy ground control is used.

Cost of outsourcing mobile LiDAR have been documented recently by Yen et al. (2014).Applied to our standard work scenario, the expected costs are shown in Table 7.7.

***Table 7.7:*** *Summary of costs for outsourcing the mobile LiDAR analysis service*

| **Item** | **Cost Estimate** | |
|---|---|---|
| | **Low** | **High** |
| Outsourcing mobile LiDAR service (rapid control) | 42,200 | 717,000 |
| Outsourcing mobile LiDAR service (high accuracy control) | 1,000,200 | 10,000,000 |

Costs of terrestrial LiDAR are also influenced by the type of equipment used, and the expected products characteristics (e.g. point density, precision, etc.). Terrestrial LiDAR is usually required for the highest point densities and highest precisions. Vincent and Ecker (2010) estimated costs as high as $29,258 per mile for this kind of survey. Applying their data to our standard working scenario we estimate the costs summarized in Table 7.8 for the "in-house" case.

***Table 7.8:*** *Summary of costs for in-house terrestrial LiDAR expertise*

| **Item** | **Cost Estimate** | |
|---|---|---|
| | **Low** | **High** |
| LiDAR data collection and analysis (high accuracy control)[1] | 100,000 | 1,000,000 |
| LiDAR data collection and analysis (rapid control)[1] | 72,000 | 760,000 |
| Annual data storage | 200 | 2,000 |
| **Total (with high accuracy control)[1]** | **100,200** | **1,002,000** |
| **Total (with rapid control)[1]** | **72,200** | **760,000** |

[1]Two sub-scenarios are considered here, depending on whether rapid or high accuracy ground control is used.

Outsourcing costs for terrestrial LiDAR have been reported by Chang et al. (2014), as summarized in Table 7.9, and fall in a similar range compared with the "in-house" cost ranges.

***Table 7.9:*** *Summary of costs for outsourcing the terrestrial LiDAR service*

| **Item** | **Cost Estimate** | |
|---|---|---|
| | **Low** | **High** |
| Outsourcing terrestrial LiDAR service | 100,200 | 1,002,000 |
| **Total** | **100,200** | **1,002,000** |

### 7.4 Digital Photogrammetry Costs

Costs for "in-house" UAV base digital photogrammetry were estimated from our experience of developing the system used in the project. Long term operation costs are somewhat uncertain, give that this is a relatively new and still emerging technology. Table 7.10 summarizes our estimates for the costs of UAV based photogrammetry applied to our standard work scenario.

***Table 7.10:*** *Summary of costs for in-house UAV SFM photogrammetry expertise*

| **Item** | **Cost Estimate** | |
|---|---|---|
| | **Low** | **High** |
| UAV | 500 | 10,000 |
| Camera | 1,000 | 4,000 |
| Computer hardware | 1,500 | 2,500 |
| Analysis software | 2,000 | 15,000 |
| Surveying equipment | 5,000 | 50,000 |
| Annual data storage | 500 | 5,000 |
| Data collection labor | 20,160 | 32,000 |
| Data processing labor | 6,720 | 10,667 |
| Ground control surveying (rapid ground control)[1] | 4,000 | 80,000 |
| Ground control surveying (high accuracy control) [1] | 10,000 | 200,000 |
| **Total (with rapid ground control)** [1] | **41,380** | **209,167** |
| **Total (with high accuracy ground control)** [1] | **47,380** | **329,167** |

[1]Two sub-scenarios are considered here, depending on whether rapid or high accuracy ground control is used.

Estimating an outsourcing cost for the UAV based digital photogrammetry is not straightforward, as such services are just now beginning to be offered, but the costs could be similar to the "in-house" option detailed in Table 7.10.

Terrestrial digital photogrammetry costs are expected to be similar to the UAV based photogrammetry, but without the cost of the UAV. Longer fieldwork required for data acquisition may however increase the costs of terrestrial digital photogrammetry, as terrestrial based photogrammetry may have less advantageous perspectives from which to acquire data. Table 7.11 summarizes our cost estimates for the "in-house" terrestrial digital photogrammetry scenario.

***Table 7.11:*** *Summary of costs for in-house terrestrial SFM photogrammetry expertise*

| **Item** | **Cost Estimate** | |
|---|---|---|
| | **Low** | **High** |
| Camera | 1,000 | 4,000 |
| Computer hardware | 1,500 | 2,500 |
| Analysis software | 2,000 | 15,000 |
| Surveying equipment | 5,000 | 50,000 |
| Annual data storage | 500 | 5,000 |
| Data collection labor | 20,160 | 32,000 |
| Data processing labor | 6,720 | 10,667 |
| Ground control surveying (rapid control)[1] | 4,000 | 80,000 |
| Ground control surveying (high accuracy control)[1] | 10,000 | 200,000 |
| **Total (with rapid control)[1]** | **40,880** | **199,167** |
| **Total (with high accuracy control)[1]** | **46,880** | **319,167** |

[1]Two sub-scenarios are considered here, depending on whether rapid or high accuracy ground control is used.

As with the UAV digital photogrammetry outsourcing case, the costs estimates are mostly hypothetical considerations, given that such services are not yet widely available, and their costs haven't been observed in a real market. Similar costs to "in-house" implementation is also expected, as described previously in Table 7.11.

Mobile digital photogrammetry is an even less explored technology than aerial or terrestrial based digital photogrammetry. Costs of "in-house" mobile photogrammetry include some of the costs discussed for photogrammetry in previous sections, but due to the different platform the type of sensor is also different. Hardware and software costs for this kind of photogrammetry are summarized in Table 7.12

***Table 7.12:*** *Summary of costs for in-house mobile SFM photogrammetry expertise*

| **Item** | **Cost Estimate** | |
|---|---|---|
| | **Low** | **High** |
| RED Epic-X Camera | 40,000 | 50,000 |
| Computer hardware | 1,500 | 2,500 |
| Analysis software | 2,000 | 15,000 |
| Surveying equipment | 5,000 | 50,000 |
| Annual data storage | 500 | 5,000 |
| Data collection labor | 20,160 | 32,000 |
| Data processing labor | 6,720 | 10,667 |
| Ground control surveying (rapid control)[1] | 4,000 | 80,000 |
| Ground control surveying (high accuracy control)[1] | 10,000 | 200,000 |
| **Total (with rapid control)[1]** | **79,880** | **245,167** |
| **Total (high accuracy control)[1]** | **85,880** | **365,167** |

[1]Two sub-scenarios are considered here, depending on whether rapid or high accuracy ground control is used.

Due to the early stages in development of the mobile photogrammetry it is difficult to estimate the cost of outsourcing this kind of service, but as with previous cases, costs may be similar to those of "in-house" development of the capabilities.

### 7.5. Benefits from each Technology and Comparison with their Costs

The ultimate goal of a cost-benefit analysis is to compare both elements (costs and benefit) in terms of their monetary value, although this can be a very complex, and sometimes controversial process (e.g. Boardman et al., 2006; Zerbe and Bellas, 2006). For the remote sensing methods that produce results in a point cloud format described in this report (i.e. LiDAR and digital photogrammetry) we will consider benefits in terms of two main criteria of value, reflecting the information content of the products derived from these methods, and which are mostly relevant to the geotechnical hazard assessment process: sampling point precision and point surface density. Sampling point precision describes how close a sampled surface point is to the real location of the surface in three dimensional space. Point surface density describes how many sampling points are retrieved per unit of surface area of the geotechnical asset that is being surveyed. In the case of InSAR, the quality of the results cannot be evaluated in terms of the

precision of point locations, but rather in terms of the precision of the measured surface displacement. The surface point density criterion is also applicable to InSAR.

Typically sampling point precision for close range (< 25 m from sensor to target) terrestrial LiDAR and photogrammetry tends to be within the 1 to 2 cm range, as has been documented in Chapters 3 and 4. This values can easily degrade to > 10 cm in the case of digital photogrammetry, if the ground control is poor, or the acquisition conditions are unfavorable. For purposes of comparison we will take the optimistic scenario of data acquisition in good conditions and use the 1 to 2 cm for the sampling point precision. Mobile and aerial LiDAR sampling point precision is usually is not as good, typically in the range of 5 to 30 cm (Shan and Toth, 2009). InSAR surface displacement precision along the line-of-sight direction is usually on the order of a few millimeters (Crosetto et al., 2010; Ferretti et al., 2011).

Point densities for LiDAR datasets depend on the setting of the scanner and the distance to the surface being scanned. Some LiDAR scanners can survey a surface at 0.01º increments, resulting in a 1.7 cm distance between points at 100 m distance. Point densities for digital photogrammetry datasets depend on the cameras sensor resolution, the focal length of the optical system, and the distance to the surface being imaged, as well as how many of the pixels in the images are chosen for re-projection onto the three-dimensional surface produced by the model. Figure 7.1 shows the distance between points as a function of distance for LiDAR and optical photogrammetry, assuming reconstruction of the surface using all the pixels.

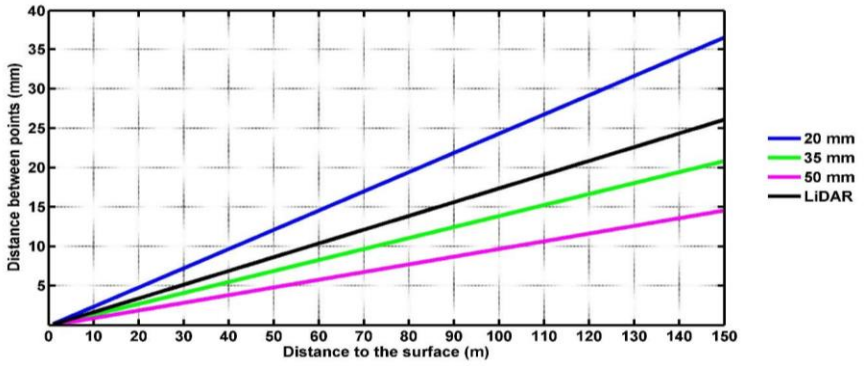


***Figure 7.1:*** *Separation between surface sample points for cases discussed in the text. LiDAR line corresponds to a 0.01º scanning increment. The other lines correspond to photogrammetry with different focal lengths, as indicated.*

InSAR point densities vary from relatively high in areas where continuous interferograms can be generated from pairs of radar images, to very sparse in areas where only staking techniques can retrieve some isolated points. In the case of continuous interferograms the point density will be limited by the radar image resolution, which typically falls in the 1 to 100 m size category. In the case of stacking methods like the PSI algorithm the densities can be much lower, and for the sites where we had successful displacement measurements (e.g. the Nevada test site), the point density was on the order of $7 \times 10^{-4}$ points per $m^2$, which would correspond to an average distance between points of ~ 38 m.

**7.6 Synthesis of Costs and Benefits**

Costs and benefits described in this chapter can be summarized in Table 7.13, although a monetary value for the benefits is not given, and only a proxy of their value, defined by the two information content criteria (precision range and point density), are given.

***Table 7.13**. Costs and benefits, described as information content, from each technology*

| Type of Survey | Cost Estimate ($) | | Precision Range (mm) | | Point Densities Range (per $m^2$) | |
|---|---|---|---|---|---|---|
| | Low | High | Low | High | Low | High |
| InSAR (In-House, persistent scatterer) | 36,700 | 287,500 | 2 | 10 | $10^{-5}$ | $10^{-2}$ |
| InSAR (In-House, interferogram) | 36,700 | 287,500 | 2 | 10 | $10^{-2}$ | 1 |
| InSAR (Outsourced, persistent scatterer) | 20,000 | 250,000 | 2 | 10 | $10^{-5}$ | $10^{-2}$ |
| InSAR (In-House, interferogram) | 36,700 | 287,500 | 2 | 10 | $10^{-2}$ | 1 |
| Aerial LiDAR | 25,200 | 541,000 | 50 | 250 | $10^{2}$ | $10^{4}$ |
| Mobile LiDAR (In-House, rapid control) | 69,560 | 1,054,100 | 50 | 300 | $10^{2}$ | $10^{4}$ |
| Mobile LiDAR (Outsourced, rapid control) | 42,200 | 717,000 | 50 | 300 | $10^{2}$ | $10^{4}$ |
| Terrestrial LiDAR (rapid control) | 72,200 | 760,000 | 10 | 50 | $10^{2}$ | $10^{4}$ |
| Terrestrial LiDAR (High accuracy control) | 100,200 | 1,002,000 | 3 | 20 | $10^{2}$ | $10^{4}$ |
| UAV photogrammetry (rapid control) | 41,380 | 209,167 | 80 | 100 | $10^{2}$ | $10^{4}$ |
| UAV photogrammetry (High accuracy control) | 47,380 | 329,167 | 30 | 50 | $10^{2}$ | $10^{4}$ |
| Terrestrial photogrammetry (In-House, rapid control) | 40,880 | 199,167 | 70 | 100 | $10^{2}$ | $10^{4}$ |
| Terrestrial photogrammetry (In-House, high accuracy control) | 46,880 | 319,167 | 20 | 50 | $10^{2}$ | $10^{4}$ |
| Mobile photogrammetry (In-House, rapid control) | 79,880 | 245,167 | 70 | 100 | $10^{2}$ | $10^{4}$ |
| Mobile photogrammetry (In-House, high accuracy control) | 85,880 | 365,167 | 20 | 50 | $10^{2}$ | $10^{4}$ |

## 7.7 Conclusions

Costs of the different remotes sensing technologies applied to geotechnical asset management vary over a wide range, depending on the type of technology and the requirements of the products expected from it. The relationship between the cost and the usefulness of the information (i.e. the benefit) obtained from those methods tends to be inverse, methods that provide more detailed and precise information tend to be more expensive. Using standard scenarios for the required work to be done it is possible to compare the different technologies at a qualitative level. The final choice between using different methods will not only be dictated by

the cost, but also by the value of the resulting information, and whether a certain type and quality of information is needed in a particular geotechnical asset management application.

In-house capabilities development vs. outsourcing of services will depend on the agencies or users budget, and the possibility of recovering the initial investment and long term operation costs, of an in-house operational system.

Methods that produce very high point densities, like LiDAR and digital photogrammetry may be necessary for applications where surface displacements change rapidly over small distances, but such methods are not very practical to apply over very large distances. Satellite based InSAR on the other hand can be applied to much larger areas, and can retrieve very small displacements, although the data point density is relatively sparse, and would not work to monitor surface displacements that change rapidly over small distances.

Consideration of all these factors, together with the costs, and in context with the agencies budget and the problem's needs for information will ultimate inform the decision of what methods are more appropriate to use in each geotechnical asset management case.

# Chapter 8: Remote Sensing Implementation Framework

The development of new approaches to administration and operation of transportation systems require the adaptation of traditional procedures and practices to the goals and methods inherent in such new approaches. Such is the case for adapting transportation agency practices to the new paradigm of transportation asset management, and a large effort has been made by federal and state agencies in facilitating such transition (e.g., FHWA, 1999; Cambridge Systematics, Inc., et al., 2002; USDOT 2015). In the case of geotechnical asset management, the adoption of such practices has been slow (Vessely, 2013), in part due to the difficulty to monitor geotechnical assets and predict the life-cycle performance.

Throughout this report we have explored, selected, and evaluated a series of remote sensing methods that show potential to be used as monitoring techniques in geotechnical asset management. Chapters 1 through 5 give an overview of the transportation asset management process and details about its implementation, as wells as the details on the remotes sensing techniques considered for geotechnical asset monitoring. In this chapter we expand on how such methods can be incorporated in a geotechnical asset management system, considering practical constraints.

## 8.1 Using Geotechnical Asset Monitoring Information and Adopting Remote Sensing Methods for Geotechnical Asset Management

### 8.1.1 Steps to Implement a Geotechnical Asset Management System

#### 8.1.1.1 Prior Work on Asset Management Implementation

Implementation of a transportation asset management system can be a challenging process. Several authors have made an effort to document and explain how the implementation process can be developed. The AASHTO report (AASHTO 2013) on transportation asset management implementation is a major milestone among such efforts. Following the initial efforts to defined and describe the concepts and practical issues behind transportation asset management (e.g. Cambridge Systematics, 1999; AASHTO 2002) it was recognized that the implementation process required a detailed, step-by-step description, resulting in the AASHTO 2013 report, which complements earlier key reports on transportation asset management. The

AASHTO 2013 report was divided in two parts, each part targeting one of two main user audiences: executive managers and practitioners. The report also includes case studies on transportation asset management implementation in a series of appendices. The report covers transportation asset management in general, but geotechnical assets require a more specific treatment, and the implementation for such a system has to be based on such specific considerations. Vessely (2013) considered the specific case of geotechnical asset management implementation, presenting many examples of asset management program that include geotechnical asset in their operation. The components of a geotechnical asset management program are also presented and compared with the actual practices at the time the report was written. A template on how to develop a geotechnical asset management program is also presented by Vessely (2013), with further recommendations on how to implement such a system in practice. It is also important to remember that geotechnical asset management should ideally not be done in isolation, it should be done as part of a large an more general transportation asset management system, and in that sense, both the general transportation asset management and the more particular geotechnical asset management approaches need to be considered in detail. The literature on asset management implementation in general, and geotechnical asset management implementation in particular has expanded since these seminal reports were published, and include some more focused and particular study case examples (e.g., Cambridge Systematics, 2009). We borrow and build upon these ideas to outline a general implementation process for geotechnical asset management that incorporates the remote sensing techniques described in this report, for asset monitoring purposes. We advise the reader to consult these reports for a more detailed treatment of the subjects outlined in this chapter.

#### 8.1.1.2 Defining Geotechnical Asset Management System Goals and Aligning them with the Agency's General Goals and Objectives

A first step in establishing a transportation asset management system is to define goals and objectives for the system, which should align with the agency's goals and objectives, AASHTO (2013) gives a detailed overview of this step. This obviously requires that the agency has clearly stated goals and objectives, which in some cases may not be explicitly defined. Assuming that such general agency goals and objectives are defined one would have to consider how the geotechnical assets contribute to such goals and objectives, and how their management

can more effectively lead the agency in achieving the goals and objectives. Starting by considering the service that a transportation system provides to the public or to specific users, one can establish performance metrics to evaluate how well the system is behaving. In transportation asset management systems it is common to state performance levels in terms of the "levels of service" standard. Characteristics such as traffic volumes, time delays and traffic congestion, road surface smoothness, and vehicle (and ultimate driver and passenger) safety are usually important variables that are subject to meet standard goals. Reaching those goals at the least possible cost is a general objective of the transportation asset management system. Many other criteria can be defined to assess the performance of geotechnical assets, for instance Table 8.1 shows a comparison of performance measures under the MAP-21 Act and the AASHTO defined performance measures. Although many of the performance measures in that table may not directly relate to geotechnical assets, establishing how the performance of a particular asset impacts those overall performance measures is a way to assess the asset's importance.

***Table 8.1:*** *Performance measures established by the MAP-21 Act and the AASHTO TAM Implementation Guide. Taken from AASHTO 2013.*

| **MAP-21 Act** | **AASHTO Implementation Guide** |
|---|---|
| Safety | Safety |
| Infrastructure | Condition |
| Congestion Reduction | Mobility |
| System Reliability | Reliability |
| Freight Movement and Economic Vitality | Mobility and Reliability |
| Environmental Sustainability | Externalities |
| Reduced Project Delivery Delays | Mobility and Reliability |
| Life-Cycle Cost | |
| Customer Measures | |

Geotechnical assets usually support other types of assets (e.g., pavement, bridges, etc.). Degradation in the performance of geotechnical assets can result in damage to other assets and their corresponding degradation in performance, e.g. excessive terrain deformation associated to geotechnical asset degradation (e.g. a retaining wall displacement) can reduce the road surface smoothness. In the most extreme cases the performance degradation of geotechnical assets can directly compromise road and traffic safety. Intermediate cases are also possible, if the damage

to the road surface is too severe or the safety is compromised, the agency may have to partially or completely shut down some road lanes, or even the entire road, until the situation is corrected.

Considering the agency's goals in operating the transportation system, the first step in setting goals for the performance of geotechnical assets is to evaluate how their performance would impact the overall performance of the transportation system, as evaluated against the agency's goals. For instance, how would excessive deformation along any segment of a system of retaining walls impact traffic volumes, or delay times, or even the safety of drivers and passengers. At this step it may be useful to look at past records of geotechnical asset related problems and estimate the impact and disruption these problems caused for a transportation network or corridor. If the frequency and magnitude of such disruption can be estimated from past events, it may be a rough approach to estimate the importance for different disruption scenarios. A more advanced treatment would include some sort of "life-cycle performance" analysis, as it is sometimes done for other types of assets, e.g. pavements, but such approaches are not possible in most cases, where information on the long term behavior and expected performance of geotechnical assets is not available. The actual assessment of such scenarios would be part of a different step in the process and will be discussed in more detail later.

#### 8.1.1.3 Defining and Prioritizing Geotechnical Assets, and Creating and Maintaining an Asset Inventory

A first step in assessing the performance of geotechnical assets is to establish what types of assets will be considered in the management system, and how they will be characterized. The variety of asset types that could be considered can be very broad. For example, depending on the terrain and other external variables, features such as slopes, both artificial and natural, can be considered geotechnical assets. Defining whether natural slopes fall within the geotechnical asset category can make a very large difference in the size of the asset inventory. Therefore, clearly defining the criteria of what elements are included in the geotechnical asset inventory is critical to the implementation of the management system. On the other hand, leaving out critical assets can also be very problematic, as their degradation and failure could have a very large and detrimental impact on the agency's goals. Guidelines provided by some authors, like Sanford-Bernard et al. (2003) and Vessely (2013) can be a starting point, but in-house expertise at the

different agencies will probably be the main resource in establishing such a classification, and deciding what items should be considered part of the geotechnical asset inventory.

Vessely (2013) for instance identified 10 types of geotechnical assets (Table 8.2). Each of these assets can be subdivided into more classes. Some types may be more critical, or their failure may have a much larger impact than others, such geotechnical assets will have priority over other assets when including them into an asset management system. Some asset types, may be very extensive, poorly delimited or difficult to define as part of an inventory, e.g. natural slopes next to a transportation corridor.

***Table 8.2:*** *Types of geotechnical assets that could be included in an asset management system. Taken from Vessely (2013).*

| **Geotechnical Asset Type** | **Reference** |
|---|---|
| Embankments and Slopes (includes rock slopes, cut slopes, landslides, and rockfall sites) | Bernhardt and others (2003)<br>Perry and others, cuttings (2003)<br>Perry and others, embankments (2003)<br>Kelly (2005)<br>Stanley and Pierson (2011)<br>American Association of Highway and Transportation Officials (AASHTO) (2011a) |
| Tunnels | Bernhardt and others (2003)<br>AASHTO (2011a) |
| Earth Retaining Structures (retaining walls, reinforced soil slopes, and earth and rock buttresses) | Bernhardt and others (2003)<br>Brutus and Tauber (2009)<br>DeMarco and others (2010)<br>Stanley and Pierson (2011) |
| Culverts or Drainage Channels | Bernhardt and others (2003)<br>DeMarco and others (2010)<br>AASHTO (2011a) |
| Foundations | Bernhardt and others (2003)<br>Stanley and Pierson (2011) |
| Pavement Subgrade | Bernhardt and others (2003) |
| Subgrade and Land within Right-of-Way | United Kingdom Department for Transport (2003) |
| Buried Reinforcing Elements, Rock Bolts, Tieback<br>Anchors, and other Buried Structural Elements | Stanley and Pierson (2011) |
| Material and Quarry Sites | Stanley and Pierson (2011) |
| Horizontal Drains | Stanley and Pierson (2011) |

A stepwise process in which different types of assets are progressively included, as the agency gains experience in the management of certain geotechnical assets, may be a way to approach the development of a geotechnical asset inventory. Developing an inventory implies a detailed survey of the entire transportation corridor network. Examples for retaining walls are given by several authors, e.g. De Marco et al. (2010) and Anderson et al. (2008). To develop the inventory a database has to be setup in an efficient way, with all relevant fields to record the asset characteristics, and to allow maintaining and expanding the database in the future. Not only is the database important for the initial inventory, but it is the base for the long term performance assessment that will be discussed in the next sections.

#### 8.1.1.4 Assess and Monitor the Performance and Health for the Assets in the Inventory

Monitoring the asset's performance and health on the long term is critical to the geotechnical asset management system. It is through such monitoring that any actions to maintain, repair, and avoid major performance degradation and related impacts, can be avoided. In the case of geotechnical assets the performance assessment can focus different characteristics of the geotechnical asset, but here we will focus on the surface displacement characteristics that could indicate that the asset performance is degrading, or worse (e.g. imminent failure or collapse).

A multi-tier system as the one described in Chapter 5 for performance monitoring can be implemented to assess the state of geotechnical assets based on their surface deformation patterns. As has been explained in that chapter (and the corresponding deliverable), the surface deformation may be related in some cases to possible asset performance degradation, but in some cases this may be difficult to infer, making the process less straightforward, and requiring more in depth analysis, possibly involving *in situ* testing and geotechnical modeling. However the hierarchical system should allow for an optimal use of resources, assigning priorities only to critical cases that could have a large impact. Performance degradation of geotechnical asset may not always be reflected by surface deformation patterns (e.g., underground erosion through hydraulic piping may not reflect as surface deformation until the damage to the asset is significant), for this reason, some asset may require other additional monitoring methods, but such cases are beyond the scope of discussion in this report.

### 8.1.2 Local and Regional Implementation using GIS Visualization and Decision Support Systems

Local and regional implementation of a geotechnical asset management system will require the visualization of the information in a geographic framework. The decision support system presented in chapter 6 provides a convenient platform to display and analyze asset performance data over a large geographic area (e. g. the first level of a hierarchical, multi-tier asset management system). The multi-tier approach has been also detailed in chapter 5, where different datasets are presented for a railroad corridor, and depending on the resolution of the dataset, different scales of analysis are required.

## 8.2 Transportation Agencies Limitations to Adopt Remote Sensing Methods for Geotechnical Asset Management, and Ways to Overcome Them

Common limitations and challenges that transportation agencies may face to adopt remote sensing methods for geotechnical asset management will include the lack of expertise on remote sensing methods and geotechnical asset management, the investment on hardware and software, and the long term nature of the benefits. Constrained by tight budgets and the need to invest resource in extensive transportation infrastructure networks, transportation agencies many time struggle to invest in activities that only will prove beneficial on the long term, and one important part in the geotechnical asset management implementation process is to build a strong case for such a long term investment.

Uncertainties in the long term outcomes of preventive maintenance, especially in cases where damaging events are less frequent (e.g. landslides), can make it hard to make a convincing argument for implementation of a geotechnical asset management system. Fortunately, extensive documentation and economic analysis in support of the long term benefits for transportation asset management can help to make a convincing argument. For other types of assets (e.g., pavements, bridges, etc.) the existing life-cycle management data help to make a solid argument, the lack of such data an models for geotechnical assets present a challenge, but the use of crude estimates of loss, disruption and other costs associated to degrading performance (or even failure and collapse) of geotechnical assets, may provide strong enough evidence for the need of managing such assets on the long term. Collecting and analyzing such data may be in itself a

difficult task, but it could be a catalytic that sparks the interest in a larger asset management program.

Costs of equipment (hardware and software), as well as technical personnel training, operators and analysts salaries, and other long term sustained costs, as shown in Chapter 7, may bring the total cost of geotechnical asset monitoring over the budgetary limits of some transportation agencies. Depending on the extensiveness of the assets to be monitored, the likelihood that monitoring will provide valuable information for intervention of critical assets, and the accessibility to the resources needed for monitoring the assets, different options may be available. "In-house" vs. outsourcing of services to acquire and analyze data on asset monitoring will depend on individual project costs, and cumulative costs over longer periods of time. If the use of a remote sensing method for monitoring a geotechnical assets is only occasional and the volume of work is relatively small, it may be more effective to outsource such a task. If on the other hand the required monitoring is extensive and has to be done very frequently, or even continuously over a large area, it may be more cost effective to develop the remote sensing capabilities as "in-house" procedures.

Developing "know-how", and human (technical and analytical) resources also implies a commitment from part of the workforce at the transportation agency. The training on many of the remotes sensing methods will not only be useful for the purposes of geotechnical asset management, but could also be used for other task within the transportation agency. Such an investment could therefore be viewed beyond the sole purpose of the geotechnical asset management system. The discussion on the other strategies to overcome the limitation and challenges of implementing a geotechnical asset management system could be expanded to the broader agency goals and objectives, but this will of course depend on the specific goals and objectives in each agency's case.

## 8.3 Examples of Remote Sensing Implementation on Case Study Sites, and Possible Expansions to a Complete Network

### 8.3.1 Unstable Slopes Asset Management Example: Hypothetical Case for the Portuguese Bend Landslide Complex (PBLC) on the Palos Verdes Peninsula in California

The Portuguese Bend Landslide Complex (PBLC), shown in Figure 8.1, is a collection of complex landslides across the rolling hills of the Palos Verdes Peninsula, southwest of Los Angeles, California. The study area, which not only includes active landslides but ground subsidence and uplift to lesser magnitudes, includes both urban and rural areas. Urban areas most notably include Rancho Palos Verdes and San Pedro, which incorporates part of the Port of Los Angeles within its city limits. Rural areas, relatively speaking, include Rolling Hills, located nearby the active landslide area (Figure 8.2).

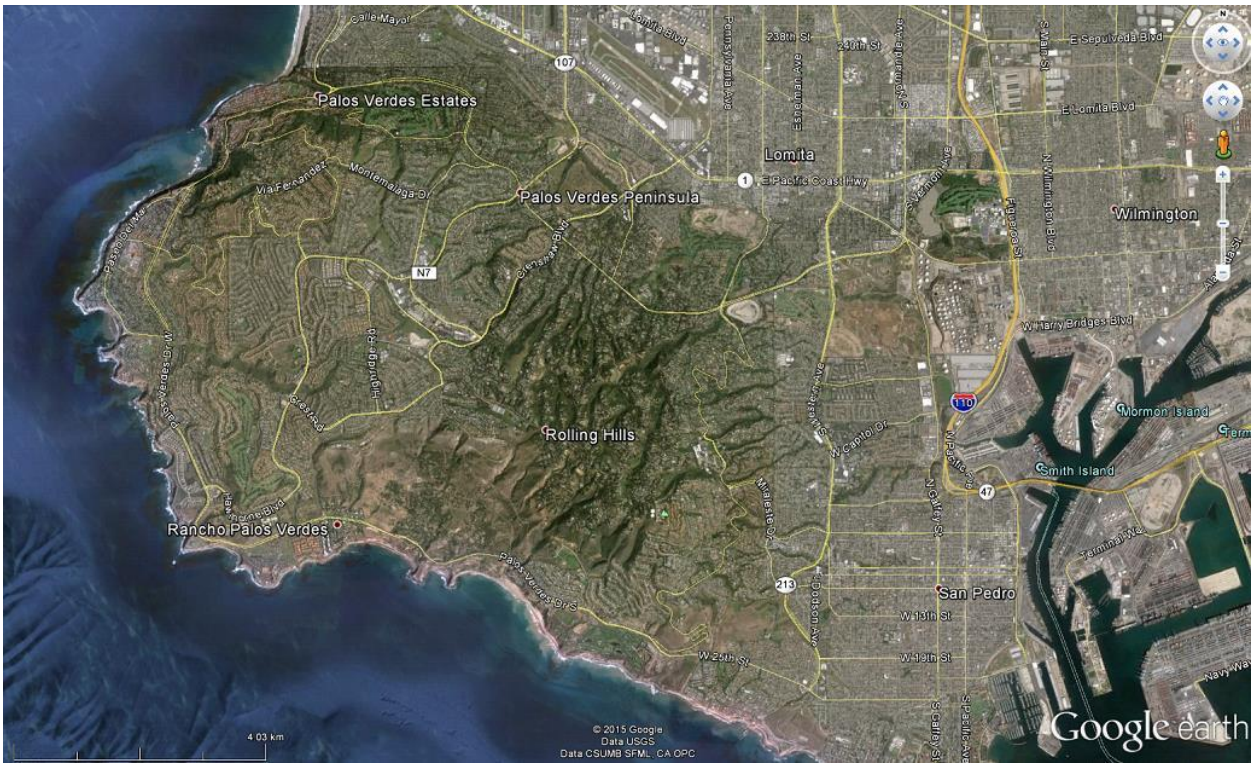


***Figure 8.1****: Palos Verdes Peninsula in California.*

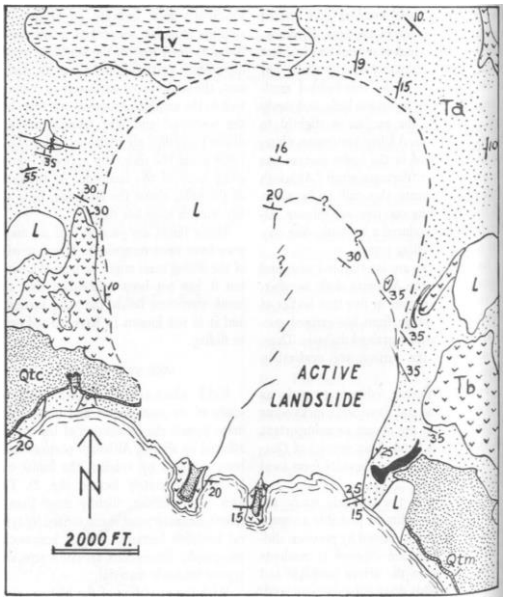


***Figure 8.2:*** *Active landslide area of the PBLC (image taken from Merriam 1960).*

In order to illustrate the implementation of a remote sensing-based geotechnical asset management approach, the following sections will include steps undertaken by the project team. Steps include defining system goals and objectives, developing a methodology to prioritize geotechnical assets, and assessing and monitoring long-term performance of the geotechnical assets. This case study was implemented by processing satellite radar imagery using the Persistent Scatterer Interferometry (PSI) technique, which is an InSAR stacking method used for monitoring small-scale (mm) deformations over long periods of time.

#### 8.3.1.1 Defining Geotechnical Asset Management System Goals for the PBLC Case, and Aligning them with the General Goals and Objectives of the Transportation Agency

The goals of geotechnical asset management is to proactively achieve and maintain geotechnical asset life-cycle performance, which include user safety, transportation corridor preservation, and minimize economic and environmental impacts of potential hazards. Geotechnical assets of interest within the Palos Verdes Peninsula include slopes (PBLC) and urban assets (e.g., bridges, retaining walls, etc.).

In order to determine the general goals and objectives of the remote sensing-based geotechnical asset management system, the project team (a term that can be replaced by *transportation agency* if implemented in the real world) conducted a literature review of

previous InSAR-related research in the region. The most recent study was conducted by Calabro et al. (2010); they utilized ERS-2 radar images to monitor seasonal fluctuations in landslide magnitudes between 1995 and 2000. Since this study focused on data acquired 16 years ago, the project team searched for synthetic aperture radar (SAR) single look complex (SLC) images more recently acquired. Two proposals were submitted to acquire high resolution satellite-based SAR SLC images. The first proposal, entitled "Using satellite remote sensing for landslide life-cycle monitoring and failure prediction," was submitted to and accepted by the European Space Agency (ESA). This radar imagery was acquired by COSMO-SkyMed, an observation satellite launched by the Italian Space Agency (ASI) in 2007.

A total of 40 high resolution radar images, acquired in the HIMAGE Stripmap mode between July 20, 2012 and September 27, 2014, were awarded. Each image covers a ground swath of 1,600 $km^2$ at a spatial resolution of 3 m. The images were then downloaded and processed with the PSI technique using SARscape, a commercially-available InSAR software. The second proposal, submitted to the Korean Aerospace Research Institute (KARI) and SI Imaging Services (SIIS), was written to obtain high resolution (3 m) KOMPSAT-5 radar images. The proposal, originally written to obtain archival radar imagery, was accepted instead as a *New Task Order Proposal*, meaning KOMPSAT-5 will obtain and transmit real-time radar images acquired over the Palos Verdes Peninsula specifically per the project team's request. This will allow for the most up-to-date satellite-based remote sensing analysis of landslides in the PBLC. KOMPSAT-5 radar images are currently being acquired (from January 1, 2016 through December 31, 2016). Since the KOMPSAT-5 images are still being acquired, the remaining implementation procedure will focus on the PSI processing results derived from the 40 COSMO-SkyMed radar images.

#### 8.3.1.2 Defining and Prioritizing Geotechnical Assets, and Creating and Maintaining an Asset Inventory for the PBLC Case

The development of a detailed geotechnical asset inventory is crucial for successful implementation of a geotechnical asset management procedure. A landslide inventory, compiled by the California Department of Conservation and the California Geological Survey, which includes all active and historic landslides in the state of California since 1965. Figure 8.3 shows the landslide inventory displaying the slope dip direction (e.g., the azimuthal direction an active

landslide would move downslope) and the Los Angeles County road system (obtained for free from the LA County web portal) in a GIS.

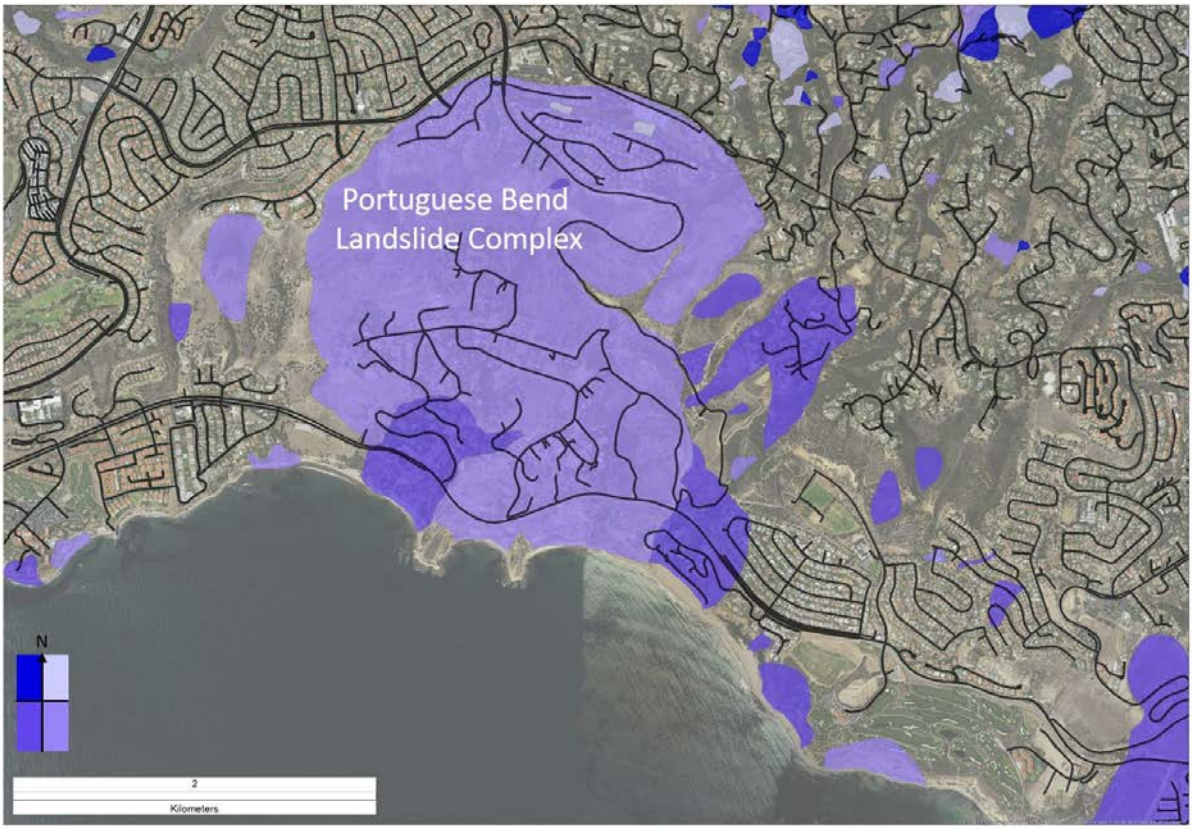


***Figure 8.3:*** *Landslide inventory, provided by the California Department of Conservation and the California Geological Survey, displayed in a GIS with roads digitized by Los Angeles County. Landslide masses are shown in various shades of blue and purple depending on the azimuthal (compass) direction of the slope dip (most slopes are dipping southward).*

#### 8.3.1.3 Assessment and Monitor of the Performance and Health for the Assets in the Inventory Covering the PBLC, using Remote Sensing Methods and GIS Visualization

Figure 8.4 shows the average velocity (mm/year) measured across the Palos Verdes Peninsula between July 2012 and September 2014. Negative values (red) indicate areas of subsidence or downslope displacements; green values (positive) indicate areas of uplift; yellow values show regions that are stable. Over 600,000 persistent scatterer (PS) points were obtained, each with detailed information regarding average velocity, total and incremental displacement,

coherence, and geographic location. Two regions of interest will be investigated: (1) the PBLC and (2) the city of San Pedro, California.

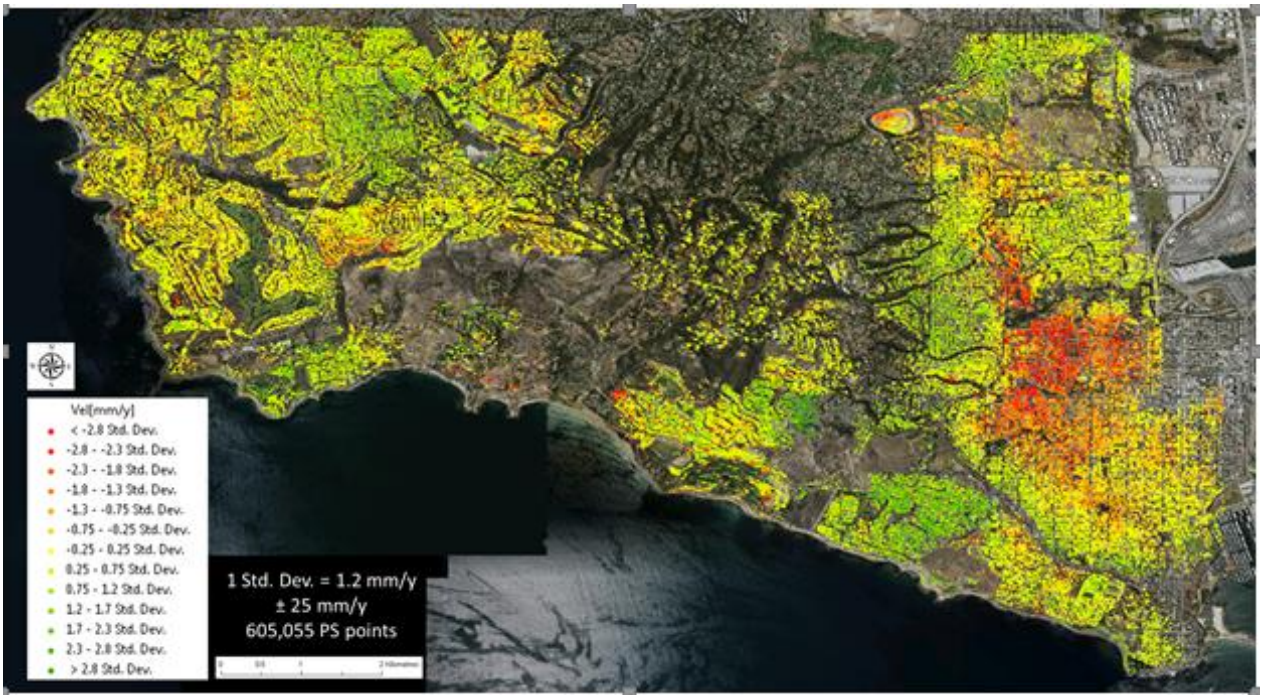


***Figure 8.4:*** *PSI average velocity (mm/year) results over the Palos Verdes Peninsula using 40 COSMO-SkyMed images (July 2012 - September 2014). Average velocity values range from -25 mm/year (subsidence or downslope movements) to 25 mm/year (uplift).*

Many separate landslides comprise the PBLC (Figure 8.3). The landslide inventory includes all landslides that occurred over the past 50 years. In order to determine which slopes are still active (e.g., are currently moving), the InSAR results from Figure 8.4 were overlaid with the landslide inventory from Figure 8.3. The result and analysis is shown in Figure 8.5. There are four regions of interest (marked with variegated dashed ovals). The white oval shows a neighborhood entirely within the PBLC. This portion of the slope appears to be somewhat unstable, with average velocity values around -5 mm/year and up to -10 mm/year on some buildings. The cyan oval marks a location where only a few structures, at the end of a cul-de-sac and located within the previous landslide boundary, experiencing average velocities in the -10 mm/year to -15 mm/year range. The red oval covers a large portion of the PBLC, near the toe of most of the slopes, where portions of the slopes are uplifting (green) while other parts of moving

downslope (red). Finally, the magenta oval shows multiple neighborhoods that appear to be moving - at average velocity rates anywhere between -2 mm/year and -20 mm/year (an order of magnitude!) - but are not located within any landslide boundary. Combining recent InSAR results with the archival landslide inventory allows for (1) a determination of which historic landslides are still active and (2) the location of any unmapped landslides, if any. This remote sensing-based geotechnical asset management approach enables the monitoring of active slopes (landslides) over the long-term.

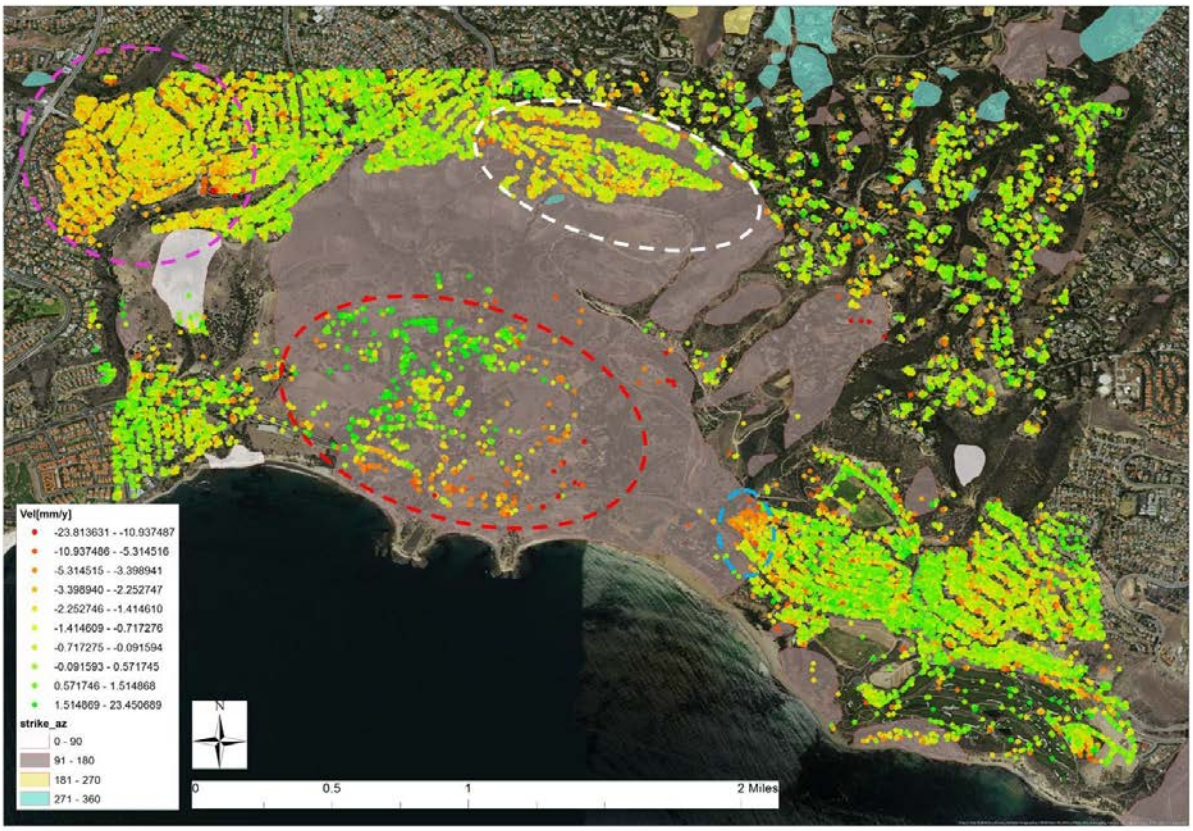


***Figure 8.5:*** *Average velocity (mm/year) of PS points obtained in the PBLC (July 2012 - September 2014). Negative values (red) indicate downslope displacement; positive values (green) indicate uplift.*

Another area of interest is San Pedro, California because it is located in what appears to be a subsidence bowl on the eastern portion of Figure 8.4. A zoomed in image of San Pedro is shown in Figure 8.6. A total of 71,267 PS points were obtained over San Pedro. A clear

subsidence trend is evident, with average velocities up to -14 mm/year measured in this region. InSAR has allowed for the detection of this subsidence trend, which can be used to alert mitigation and construction field crews to the potential damage to transportation and geotechnical assets, especially near the 'edges' of the subsidence trend where the greatest deformation differential is measured.

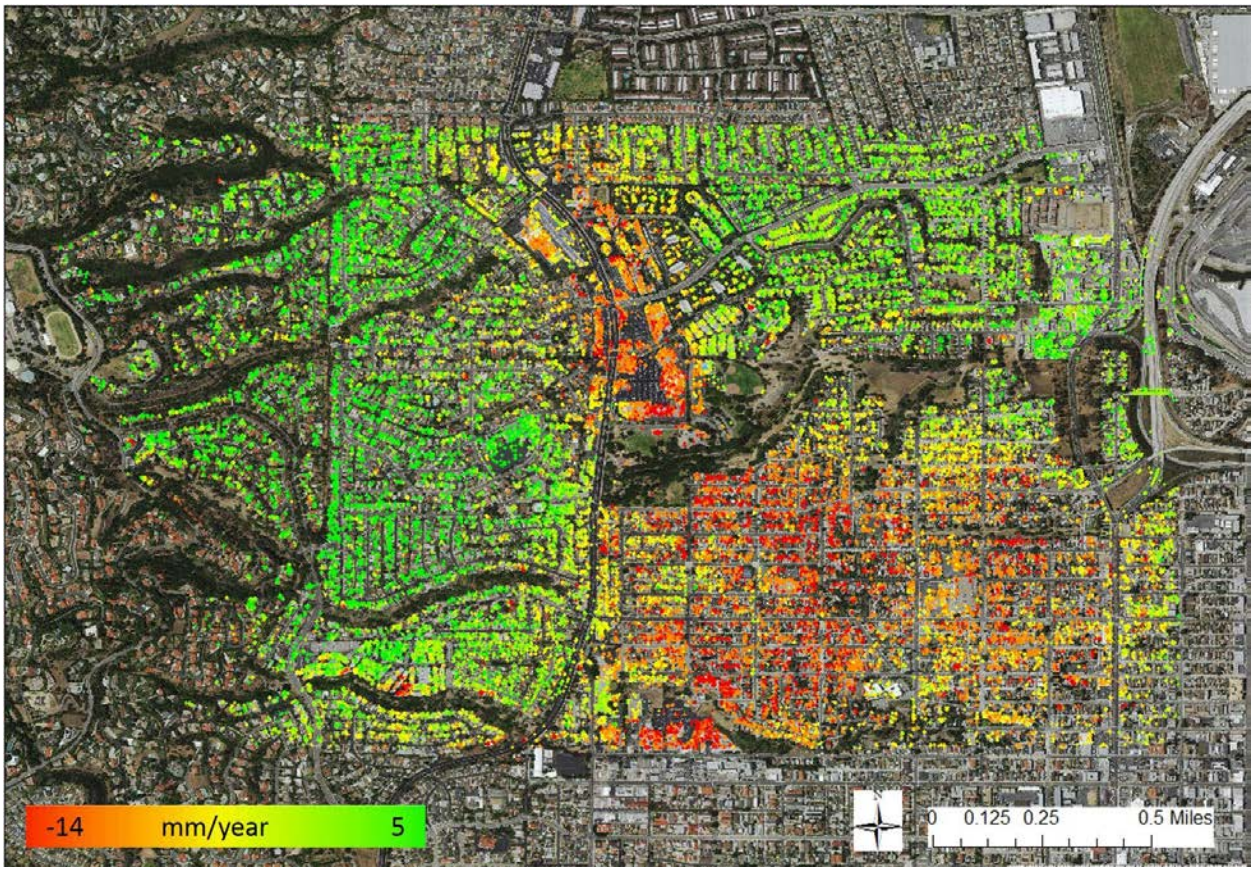


***Figure 8.6:*** *Average velocity (mm/year) of 71,267 PS points obtained over San Pedro (July 2012 - September 2014). Negative values (red) indicate subsidence; positive values (green) indicate uplift.*

Successful implementation of a remote sensing-based geotechnical asset management approach requires relevant software (e.g., GIS and other software required for data processing), training for the staff, and resources to review and update asset inventories and life-cycle conditions throughout the transportation network. This regional approach, as shown using InSAR

to identify locations of greatest asset deterioration, is a great first step towards a multi-tiered geotechnical asset management procedure.

The next section shows a hypothetical case for retaining walls located along the M-10 highway in southeastern Michigan - a more local-scale geotechnical asset management approach.

### 8.3.2 Retaining Wall Asset Management Example: Hypothetical Case for the M-10 Site

The study case for the M-10 highway presented in Chapters 4 and 5 will be used as a hypothetical example in this section, to illustrate how the different components of the geotechnical asset management system could be implemented, focusing on the remote sensing monitoring techniques.

#### 8.3.2.1 Defining Geotechnical Asset Management System Goals for the M-10 Highway Case, and Aligning them with the General Goals and Objectives of the Transportation Agency

The agency in charge of the M-10 Highway transportation corridor is the Michigan Department of Transportation, and they define a comprehensive set of goals, objectives and performance measures, as part of their strategic planning (Wilbur Smith Associates, 2006). Goals include preservation of transportation assets, safety to transportation users, basic mobility, and some other goals. For this example we could focus on the preservation and safety goals, as they apply to potential failure of geotechnical assets along the M-10 Highway.

The M-10 Highway transportation corridor includes a wide variety of transportation assets, and provides meets the transportation needs of a large user population (Cerminaro, 2014). Geotechnical assets include amongst others, a series of retaining walls, as described in Chapter 4, and by Cerminaro (2014). The main function of the retaining walls is to provide structural support to the fill material that bounds the depressed highway, and constitutes the terrain for the adjacent service road. This function would be compromised if such structural support was lacking. Failure of the retaining walls would compromise the depressed highway (M-10) and the adjacent service road, and even possibly the neighboring residential areas.

Performance degradation could go from minor deformation that would be unnoticeable to the common transportation system users, to potentially catastrophic collapse of the wall system, which would put the users at risk of injury or death. In between the extreme cases there is a wide

range of possible scenarios, from minor traffic interruptions required for repairing the walls and other assets that may be affected by its performance degradation (e.g. the service road surface smoothness), to total closure of the highway needed for major repairing work. Given the importance of the M-10 Highway (e.g. traffic volume) and the magnitude of the potential impacts, it becomes evident that maintaining the functionality of the retaining wall system is in line with the agency goals, at a high priority. For details on the importance of the M-10 highway and the potential disruption that a failing retaining wall system could cause see Cerminaro (2014) and references therein.

#### 8.3.2.2 Defining and Prioritizing Geotechnical Assets, and Creating and Maintaining an Asset Inventory for the M-10 Highway Case

Although the M-10 highway transportation corridor includes a very broad set of transportation assets, it could be argued that retaining walls, are amongst the most important geotechnical assets in this corridor. Foundations, pavement subgrade and other geotechnical assets could also be very important, but for the sake of the example we will only consider the retaining walls. Although currently the Michigan Department of Transportation lacks a comprehensive inventory of retaining walls, they recently have moved to develop such an inventory for the whole state. Such an effort would follow a similar procedure to that of retaining wall inventories that have been developed for other agencies, e. g. De Marco et al. (2010) and Anderson et al. (2008).

#### 8.3.2.3 Assessment and Monitor of the Performance and Health for the Assets in the Inventory Covering the M-10 Highway, using Remote Sensing Methods, and GIS Visualization and Decision Support Systems

Following the multi-tier approach to monitoring and managing geotechnical assets outlined throughout this report, a first level analysis would require a broad assessment and monitoring of the entire M-10 highway corridor. The initial assessment would be carried out as part of the inventory development, and would include visual inspection of the conditions for the different wall sections along the M-10 corridor. Large scale monitoring at this point could include surface displacement monitoring through InSAR, as described in Chapter 4 for this site.

The InSAR monitoring did not yield any significant results for the particular M-10 case that we are considering, although other sites did show movement in that area. For this reason, other methods may be necessary for monitoring asset performance. In the case of the M-10 retaining walls, the identification of the problem came from visual inspection, after excessive wall movement was observed and reported to the Michigan Department of Transportation. It is however also possible to apply some of the other remote sensing techniques described in this report, to identify such potential problems.

Once a possible problem has been identified (e.g. excessive retaining wall movement), a more detailed monitoring is necessary to assess the need for major intervention measures. In the case of the M-10 retaining walls, the Michigan Department of Transportation applied a series of traditional surveying methods to track the wall displacement overt time, but some of the remote sensing techniques described in this report could also have been used. In fact, we applied the digital photogrammetry method and obtained high quality measurements of the wall relative displacement, as described in Chapters 4 and 5.

The geotechnical asset monitoring information collected through remote sensing and other methods needs to be processed and analyzed. A GIS based decision support system, like the one described in chapter 6 could serve for this purpose. Surface displacement information from InSAR and other sources can be displayed in the GIS interface for the entire M-10 corridor. As more detailed monitoring is done on specific sites, this information is concentrated in those areas, with the system allowing to "zoom in" onto the regions of interest.

## 8.4 Conclusions

The implementation of a geotechnical asset management system requires several important actions to be taken. Documentation on how to implement transportation asset management systems have been explored by several authors. AASHTO (2013) describes the process in general and Vessely (2013) focuses on geotechnical asset management systems in particular; such work forms the basis for topics discussed in this chapter. Defining the asset management goals and matching them to the transportation agency's goals and objectives is key to fully engage the agency in pursuing such a management system. Creating an asset inventory and a monitoring and performance assessment program for the assets are also necessary steps. The implementation process needs to be considered in the context of the agency's limitations and

constraints, and keeping in mind strategies to overcome such limitations and constraints. Some of the implementation aspects were illustrated with two case study examples, and a more in depth description of such cases is given in other chapters throughout the report.

## Chapter 9: Outreach Activities

### 9.1 Introduction

Outreach activities for the project aimed to spread awareness about geotechnical asset management in general, and the use of remote sensing technologies in particular. After researching the potential users for such technologies and considering the type of agencies and companies that would engage in geotechnical asset management, we focused our efforts on developing multimedia material targeting potential users of the technology. The multimedia content was designed to match our experience with developing the methods throughout the project, and we included examples from the fieldwork cases we investigated. Outreach activities also included direct contact meetings with project partners, to discuss the project's progress and their involvement with it.

### 9.2 Outreach Video on Remote Sensing and Geotechnical Asset Monitoring

To convey the potential use and benefits of using monitoring remote sensing methods for geotechnical asset management, a video was produce, explaining how the methods work, and the potential results that can be obtained with them. Video production was done by the Michigan Tech CinOptic Team. Preparation for video production began in early 2014, through a series of meeting in which the video's goals and general content were defined, defined in a strategic media and outreach plan.

Video footage from fieldwork done as part of the project was collected in July and August of 2014, at the Nevada and Alaska sites. Two CinOptic team members participated in the fieldtrips and obtained 8 days' worth of footage of the different aspects of fieldwork, the site conditions, and the partial results obtained in the field. Other multimedia material collected during the fieldtrips include photographs, video, interviews and audio captures.

Several individual videos, exploring the specific techniques (i.e., InSAR, LiDAR, photogrammetry) were produce separately, to address the specific communication needs for each method. Originally the idea was to create a self-contained CD-type product, with a menu for the individual videos, from which the viewer could navigate and choose what to watch, but this idea was later change in favor of an on-line version which would not require a CD-reader, and could

be watched in many more platforms. A dedicated YouTube channel was created, and a 7 videos watch list was uploaded.

The video list opens with an introductory video about sustainable asset management applied to geotechnical assets. This short video includes interview clips with experts (e.g. Billy D. Connor, Director of the Alaska University Transportation Center), as well as background footage of the fieldwork conducted under the project, showing different types of assets. The video can be seen via this link: https://youtu.be/Qws3quO8fFs

Three videos explain the InSAR, LiDAR and photogrammetry applications to geotechnical asset management. A video on InSAR technology explains how the use of satellite based InSAR application can be used to measure very small surface displacements over extensive areas. Clips from interviews with team members that analyzed the InSAR imagery used in the project, and who discuss the use of InSAR for geotechnical asset management are presented, with background videos and animations that illustrate how the methods works. Extensive use of videos and animations produced by the European Space Agency (ESA) is included in this video and enhances its visual value, the ESA operates several of the satellites that produce the radar images that can be used for InSAR monitoring of surface displacements. Clips of the processing routines were also incorporated in the video. The video can be seen via this link: https://youtu.be/W-qyvXIIaxU

The LiDAR video also discusses how the technology can be used to monitor geotechnical assets as part of a geotechnical asset management system. Interviews with team members who worked on the LiDAR processing and analysis are complemented with field views of the data acquisition process and animations of how the scanning process works. Videos and animations from third parties (outside the project) were also used with their permission, to better illustrate some of the points described in the video. The video can be seen via this link: https://youtu.be/4ealmg_fL2s

The digital photogrammetry video follows a similar theme as the two previous videos. The technique is broadly explained by the team experts who collected, processed and analyzed data for the project. Videos from the field work and actual videos taken from the acquisition platforms (e.g. aerial UAV), and are used to illustrate such procedures. Video clips of the data processing are also included in this video, with a background interview voice explaining some aspects of the processing. Processing results (e. g. point clouds) are also shown to illustrate the

types of results obtained from the model. This video can be seen via this link: https://youtu.be/uulqJb9aWBI

To familiarize the viewer with more concrete applications of the methods, two study cases were summarized and presented in video format as well. A local case study for the M-10 highway retaining walls study, in Detroit, Michigan, and a regional case study for the southeast Nevada railroad corridor study. The M-10 Highway retaining wall study focusses on the use of digital photogrammetry applied to measure surface displacements of retaining walls. Details of the data acquisition, processing an analysis are given in an interview format, by the team members who participated in this part of the project. The video makes use of illustrations of the processing, photographs of the data acquisition, and imagery and videos of the results, using three-dimensional descriptions of the data that would otherwise be difficult to explain in written or with two-dimensional figures. The video also includes some examples and results from our laboratory experiments on scaled models, as they were relevant to this part of the work. The video can be seen in this link: https://youtu.be/p61b6h0I_zs

The regional case study gives a broader overview of the application of the methods for monitoring geotechnical assets on a railroad corridor, specifically the potential movement of rock slopes, as potential precursors to slope instabilities and rock-slides. The video also puts the methods in the broader context of geotechnical asset management. Interview with project members who participated in the data collection, processing and analysis are combined with videos of fieldwork, data processing and results. The video can be seen in this link: https://youtu.be/fS1u9aIyOCk

Finally, a short video with additional interviews of experts and team members, describing the advantages, potential uses and limitations of the application of remote sensing methods to geotechnical asset management is also presented, to complement the other videos. Interviews are combined with fieldwork video and data processing and results illustrations. The video can be seen here: https://youtu.be/3odYSiQlNmk

Production work for all these videos followed professional standard practices. Extensive interviewing (several hours total) of experts and project participants was collected and thoroughly edited to extract only the most informative and relevant clips for the intended content of the video. To capture the viewers' attention and give a more pleasant and easy deliverance of the message content, the editing of the interviews was coupled with field videos and illustrations

of the data acquisition, processing and results, to overlay relevant videos on the interview audio. Although the audio was entirely based on the interviews, the interviewees appear only for short periods on screen, alternating this with videos of fieldwork, etc. This visual alternations helps keep the attention of the viewer and helps to better illustrate the topic being discussed. Figure 9.1 shows a screen capture of two of such editing sessions.

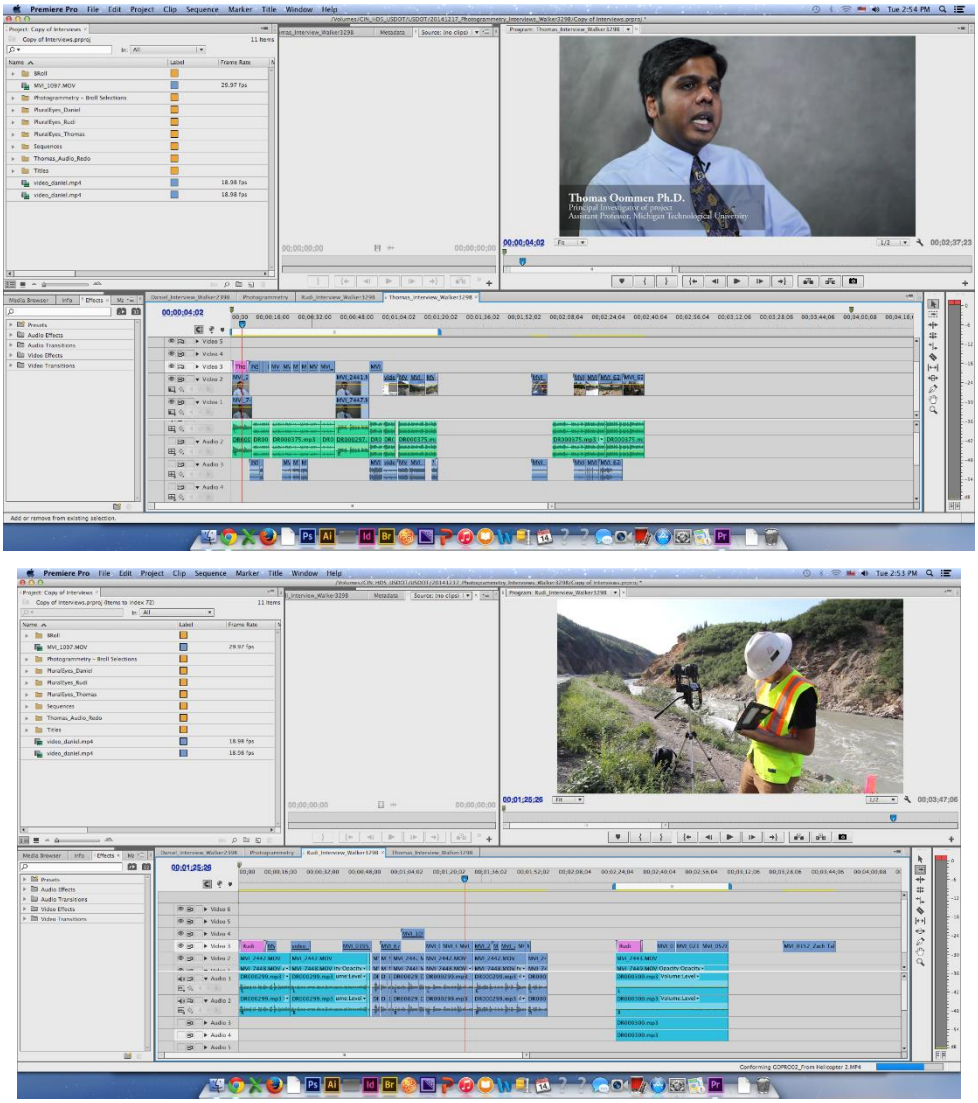


***Figure 9.1:*** *Screen captures of the video editing process in which interview audio is combined with fieldwork video.*

The videos also make extensive use of other types of illustrations and clips, including those provided by third parties (e.g., ESA, Riegl, etc.). An effort was made to provide the most relevant visual illustrations corresponding to the interview topic being discussed in the audio. A balance between the animations, field or processing videos, and the actual interviewee's face being displayed is important, to keep the viewers' attention focused, but also make this material personal and understandable. Figure 9.2 shows some screen captures of video illustrations and interview faces during the editing process.

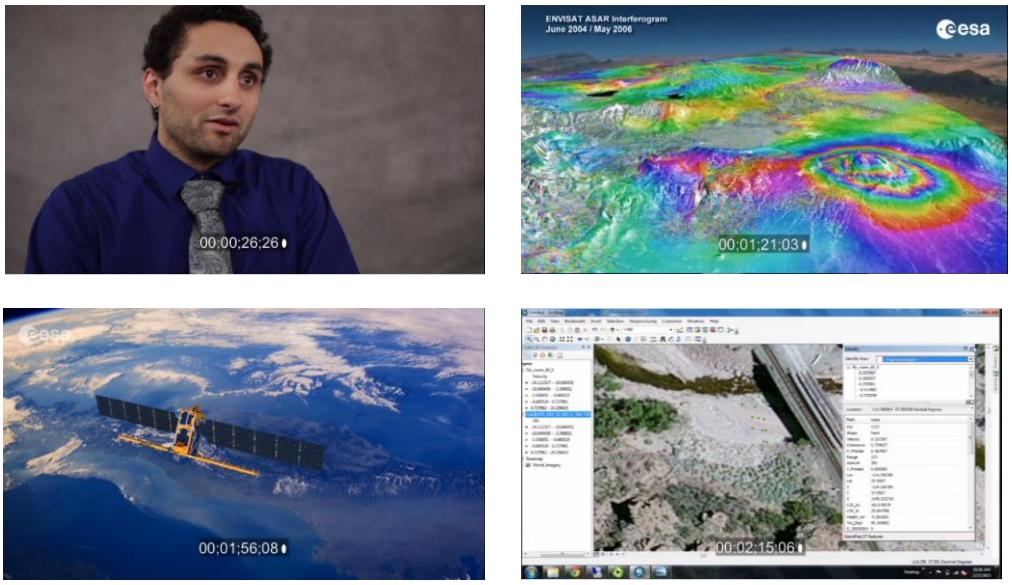


***Figure 9.2:*** *Screen captures of different video illustrations for the InSAR video.*

The channel with all the videos can be accessed here: **http://mtri.org/geoasset/outreach/**

### 9.3 Outreach Activities with Project Partners

A series of meetings with project partners (Alyeska, Union Pacific, etc.) were held throughout the project, to inform them on the status of the project, the partial results and to plan joint fieldwork and data sharing. Figure 9.3 shows a series of slides presented to the Union Pacific project partners at one of the meetings. This meetings facilitated a two-way exchange of ideas and a broader discussion of how the results of the project could be applied to geotechnical asset management. Important input into the projects development by the partners was also incorporated from these meetings.

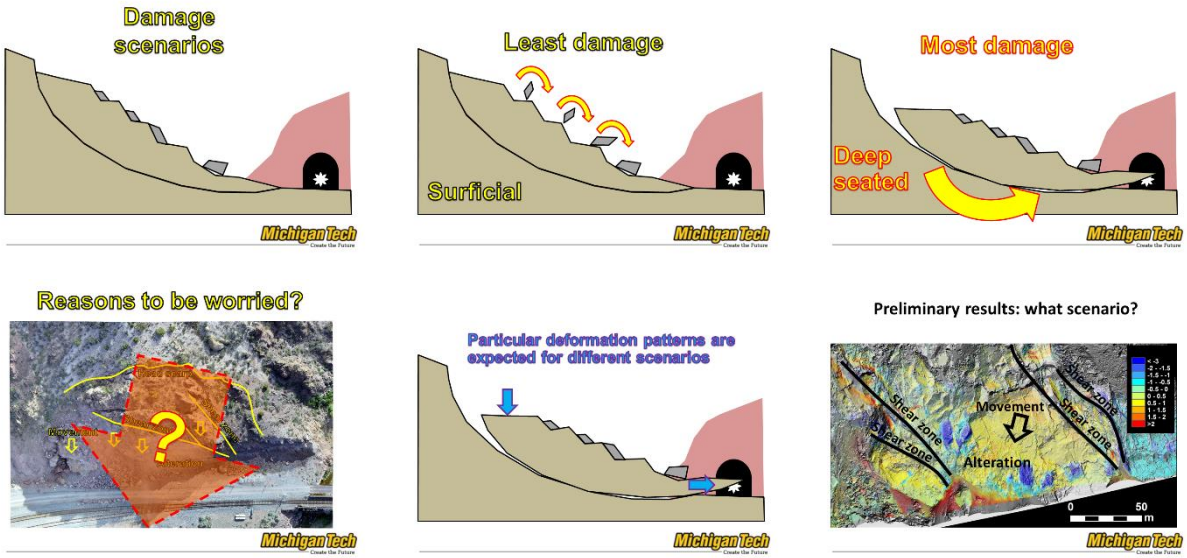


***Figure 9.3**: Example of slides from the presentation given to the head of geotechnical engineering at Union Pacific. The slides describe different possible scenarios of slope instability at the Nevada site, and how surface change analysis can help to constrain the likelihood of those scenarios.*

Other outreach activities included press releases by Michigan Tech University, that were also replicated by other parties, e.g. AEG. Figure 9.4 shows a screen capture of a press release by Michigan Tech University (http://www.mtu.edu/news/stories/2014/october/stabilizing-geotechnical-assets-new-research-aims-identify-potential-highway-railroad-problems.html), and the corresponding mention by AEG insider: http://www.multibriefs.com/briefs/aeg/103014.html.

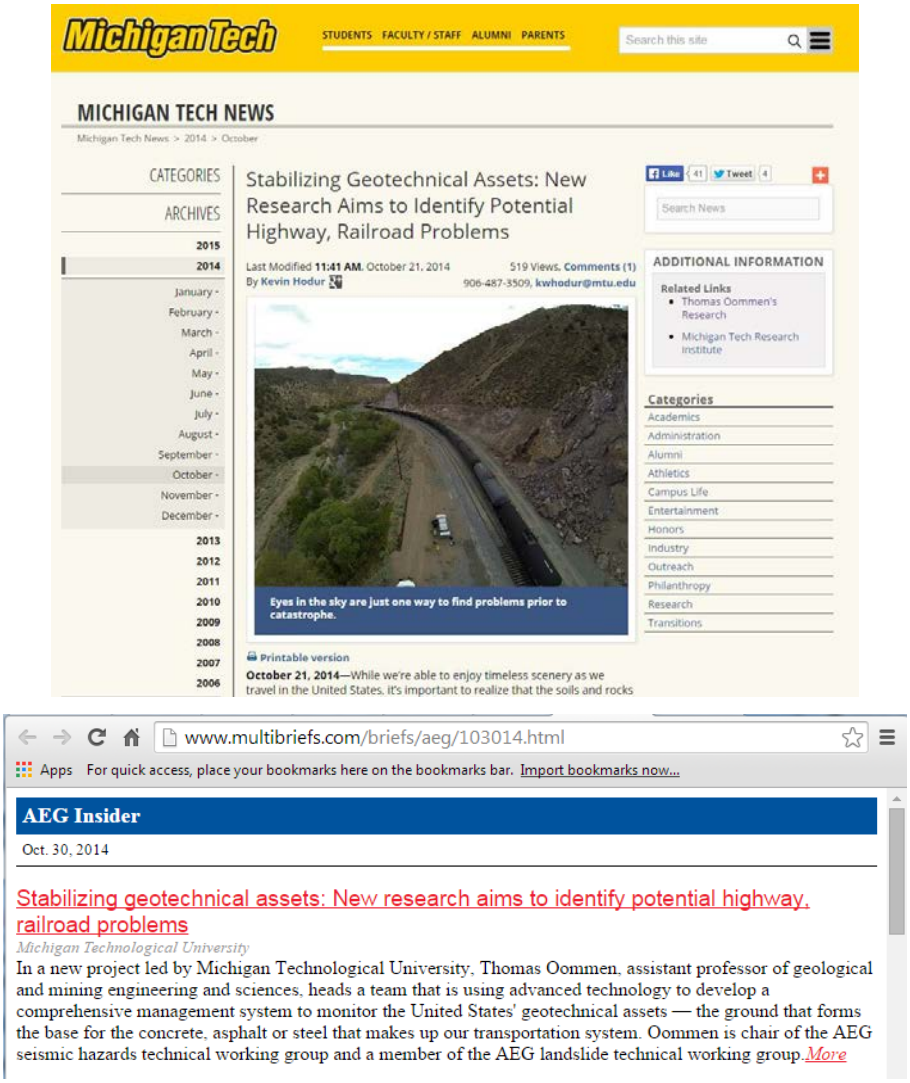


***Figure 9.4:*** *Screen captures of a press release by Michigan Tech University (upper panel) that was also feature by AEG insider (lower panel).*

## 9.4 Conference Presentations and Publications

A series of conference presentations, posters and published articles were also delivered during the project, and more products like these are expected in the near future. Presentations at conferences are important to share the projects results with potential users in academia and industry, and provide an alternative to disseminate the results to a broader audience, who may not otherwise come across this information, if it was only published as project deliverables and

reports. Following is a list of conference presentations and posters, and journal articles on the project's results.

- Bouali, E.H., Oommen T., Escobar-Wolf R., and Douglas C.S. (2014) An application of interferometric synthetic aperture radar in a railroad corridor 2014 Annual Technical Forum on Geohazards Impacting Transportation Aug 6-7, 2014. Lexington, Kentucky.
- Cerminaro, D., Oommen T., Escobar-Wolf R., Vitton S., Dobson R.J., Brooks C.N., and Endres R.B. (2014) Proactive assessment of retaining walls along transportation corridors using optical remote sensing 2014 Annual Technical Forum on Geohazards Impacting Transportation Aug 6-7, 2014. Lexington, Kentucky.
- Bouali, E.H., Escobar-Wolf R., and Oommen T. (2014) Interferometric synthetic aperture radar applied to geotechnical asset management in transportation environments 57th Annual Meeting of the Association of Environmental & Engineering Geologists, Scottsdale, Arizona Sep 20-28, 2014.
- Cerminaro, D., Oommen T., Escobar-Wolf R., Vitton S., Dobson R.J., Brooks C.N., and Endres R.B. (2014) Monitoring retaining walls along transportation corridors using optical remote sensing 43rd ANNUAL FHWA MIDWEST GEOTECHNICAL CONFERENCE Oct 1-3, 2014. Bloomington, Minnesota.
- Invited talk at the Department of Civil Engineering Seminar, University of Texas, Arlington, Texas "Sustainable Geotechnical Asset Management Along the Transportation Infrastructure Environment" (October, 2014)
- Invited talk at the Department of Civil Engineering Seminar, University of Michigan, Ann Arbor, Michigan "Sustainable Geotechnical Asset Management Along the Transportation Infrastructure Environment" (November, 2014).
- Cerminaro, D., 2014. Implementation of Photogrammetry to improve proactive assessment of retaining walls along transportation corridors. Master Degree Thesis (Civil Engineering). Michigan Technological University. 68 pp.
- Justice, S. M. 2015. Application of a hazard rating system for rock slopes along a transportation corridor using remote sensing. MS Thesis, Michigan Technological University. 89 pp.

- Bouali, E.H.Y., Oommen, T., Escobar-Wolf, R.P., 2015, Field verification of satellite-based velocity data, the 49th annual meeting of The Geological Society of America North-Central Section Meeting, 19-20 May, Madison, Wisconsin, United States.
- Bouali EH, Escobar-Wolf R, Oommen T, 2015, Ground Feature Monitoring Using Satellite Imagery: How Interferometric Stacking of SAR Can Mitigate Geo-Disasters along Transportation Corridors, ASCE GEOSTRATA, 2015(4), 38-44.
- Bouali EH, Oommen T, Escobar-Wolf R, 2015, Can we extract information regarding transportation asset condition from satellite-based radar interferometric data? 58th annual meeting of The Association of Environmental & Engineering Geologists, 19-26 September, Pittsburgh, Pennsylvania, United States.
- Bouali EH, Oommen T, Escobar-Wolf R, 2015, A multi-sensor approach to monitor slope displacement. American Geophysical Union annual meeting, 14-18 December, San Francisco, California, United States.
- Oommen T, 2015, Sustainable geotechnical asset management along the transportation infrastructure environment, Van Tuyl Lecture, Colorado School of Mines, October 2015, Golden, Colorado, USA.
- Bouali EH, Oommen T, Escobar-Wolf R, 2016, Interferometric stacking toward geo-hazard identification and geotechnical asset monitoring, *Journal of Infrastructure Systems*, 22(2), doi: 10.1061/(ASCE)IS.1943-555X.0000281, 05016001.
- Bouali EH, Oommen T, Vitton S, Escobar-Wolf R & Brooks C, 2016, Remotely-sensed imagery and field data used for a Rockfall Hazard Rating System, *Environmental and Engineering Geoscience*, under review (submitted February 29, 2016).
- Bouali EH, 2016, Monitoring slope instability and ground deformation across the Palos Verdes Peninsula with COSMO-SkyMed satellite radar imagery, Michigan Technological University 2016 Graduate Research Colloquium, February 24-25, Houghton, MI.
- Bouali EH, Oommen T & Escobar-Wolf R: Structure Mapping through Spatial and Temporal Deformation Monitoring using Persistent Scatterer Interferometry and Geographic Information Systems. Abstract submitted on March 7, 2016 to present a paper at the 2017 Geotechnical Frontiers Conference in Orlando, Florida on March 13-16, 2017.

## 9.5 Project Website

A web page with information on the project's development and progress was also created for outreach purposes (see figure 9.5). The webpage includes a general project description that summarizes the original project's proposal, including the objectives, the planned activities and the expected outcomes and products. A section on video outreach hosts the videos described in section 10.2, and a timeline of the project describes how it has been executed. The tasks and deliverables were also described in detail in one section, to give a more thorough idea of what the project aims to accomplish. Information on the team members and their email contacts is also provided, as well as the institutions that they represent. The Technical Advisory Committee is also listed. Some of the project products (e. g. deliverables) are also displayed and available for download.

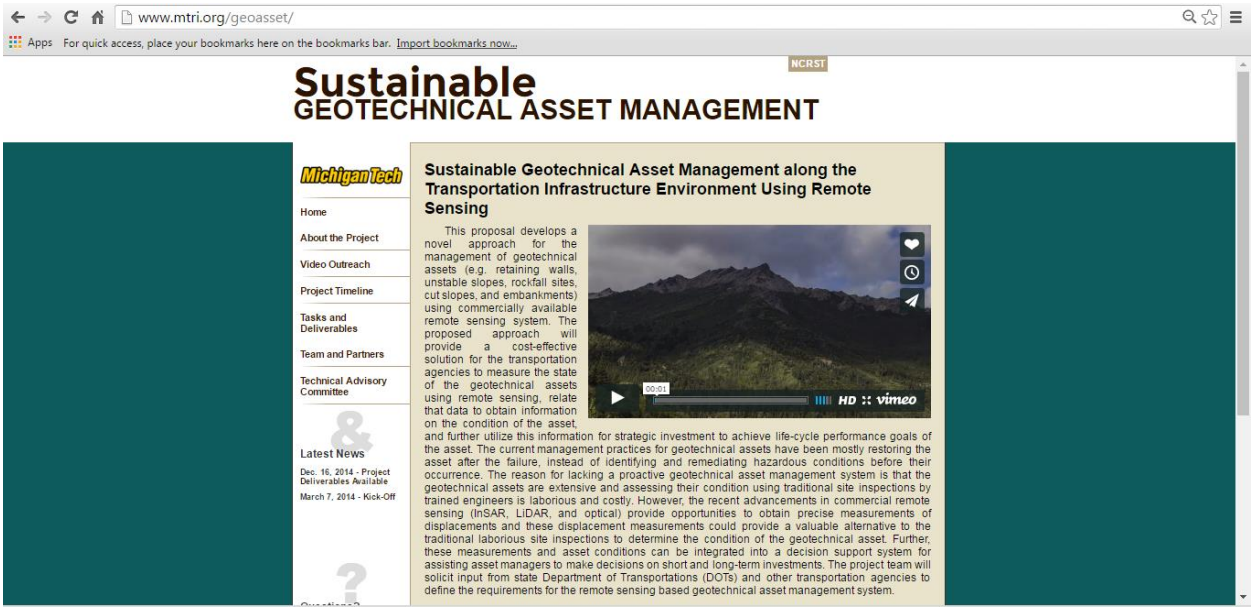


***Figure 9.5****: Screen capture of the home page of the project's webpage.*

The project's webpage can be accessed here: http://www.mtri.org/geoasset/

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**Appendix: Deliverables:**

**Available from: http://www.mtri.org/geoasset/tasks/**

**1-A: Requirements for Remote Sensing Based Geotechnical Asset Management System including Types of Geotechnical Assets and their Conditions that need to be assessed in Different Transportation Environments**

**2-A: Candidate Remote Sensing Techniques for the Different Transportation Environments, Requirements, Platforms, and Optimal Data Fusion Methods for Accessing the State of Geotechnical Assets**

**3-A: report "Evaluation of the selected remote sensing techniques to assess the state of geotechnical assets and performance validation with historic geotechnical data"**

**4-A: A report titled "Performance rating of geotechnical assets using remotely measured displacement"**

**4-B: A demonstration of how the displacement measured using remote sensing along with other site variables can be used to access the condition of geotechnical assets along the transportation corridor "Performance modeling of geotechnical assets using remote sensing inputs: A geotechnical asset rating tool (GART)"**

**5-A: A report describing the requirements of the GAMDSS based on project expertise and TAC input, entitled "Geotechnical Asset Management Decision Support System Requirements."**

**5-B: A report detailing the GAMDSS software acquired or developed during this project, entitled "A Review of the Geotechnical Asset Management Decision Support System (GAMDSS)."**

**6-A: Cost benefit analysis of a proactive geotechnical asset management system using remote sensing**

**7-A: A report titled "An implementation framework of the key project tasks for State DOTs/operators/owners"**

**7-B: A report describing the specific outreach components completed as part of activity 11, including descriptions of the results identified in the seven-part comprehensive outreach program described in the activity outputs.**