A PLATFORM FOR PROACTIVE RISK-BASED SLOPE ASSET MANAGEMENT – PHASE I

INTERIM PROJECT REPORT

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16. Abstract
Unstable slopes, including landslides, rock falls, and debris flows, present significant risk to safety and regional commerce, and present a chronic concern for highway mangers. Due to the widespread spatial and temporal distribution of these hazards, most states have, or are taking, measures to manage slopes along their highway alignments. However, given the physical nature of slopes along highway corridors, they pose a number of challenges when deciding where to allocate funds; from a system-wide asset management perspective. Slope assessment has traditionally been laborious and costly but altogether necessary due to the potential consequences of a failure. Current best-practices for management do not necessarily facilitate proactive slope management – identifying and remediating hazardous conditions before a failure occurs. The goal of this project is to develop a platform that will facilitate an objective and proactive programming of DOT resources for rock-slope assets within highway corridors. The platform developed in this project is intended to be a risk-based administrative tool that will enable highway owners to make informed decisions on how best to program resources related to rock-slope inspection and remediation.

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List of Abbreviations

AKDOT&PF: Alaska Department of Transportation and Public Facilities
ALS: Airborne laser scan or Airborne LiDAR system
BIL: Band Interleaved by Line
CORS: Continuously Operating Reference Stations
DEM: Digital Elevation Model
DMI: Distance Measurement Indicator
DOP: Dilution of Precision
DSM: Digital Surface Model
DTM: Digital Terrain Model
DSS: Decision Support System
GAM: Geotechnical Asset Management
GNSS: Global Navigation Satellite System
GPS: Global Positioning System
Hz: Hertz
IMU: Inertial Measurement Unit
INS: Inertial Navigation System
KMZ: Zipped KML (Keyhole Markup Language)
LiDAR: Light Detection and Ranging
MAP 21: Moving Ahead for Progress in the 21st Century Act
MSE: Mechanically Stabilized Earth
MLS: Mobile Laser Scan
MP: Mile Post
NCHRP: National Cooperative Highway Research Program
OLS: Ordinary Least Squares
ODR: Orthogonal Distance Regression
OPUS: Online User Positioning Service
PacTrans: Pacific Northwest Transportation Consortium
PBV: Point Bounding-Box Vertex
PDOP: Positional Dilution of Precision
PPK: Post Processed Kinematic
RDA: Rockslope Deterioration Assessment
RGB: Red Green Blue
RHRS: Rockfall Hazard Rating System
RINEX: Receiver Independent Exchange
RMS: Root Mean Square
RTK: Real Time Kinematic
TAM: Transportation Asset Management
TIN: Triangulated Irregular Network
TLS: Terrestrial Laser Scan
WSDOT: Washington State Department of Transportation

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Abstract

Unstable slopes, including landslides, rock falls, and debris flows, present significant risk to safety and regional commerce, and present a chronic concern for highway mangers. Due to the widespread spatial and temporal distribution of these hazards, most states have, or are taking, measures to manage slopes along their highway alignments. However, given the physical nature of slopes along highway corridors, they pose a number of challenges when deciding where to allocate funds; from a system-wide asset management perspective. Slope assessment has traditionally been laborious and costly but altogether necessary due to the potential consequences of a failure. Current best-practices for management do not necessarily facilitate proactive slope management – identifying and remediating hazardous conditions before a failure occurs. The goal of this project is to develop a platform that will facilitate an objective and proactive programming of DOT resources for rock-slope assets within highway corridors. The platform developed in this project is intended to be a risk-based administrative tool that will enable highway owners to make informed decisions on how best to program resources related to rock-slope inspection and remediation.

Chapter 1 Introduction

Executive Summary

A long-term concern of highway managers is unstable slopes (i.e., landslides) along transportation corridors. Instabilities create safety risks and impact regional commerce, even if events occur infrequently. The infrequency of slope movement is a factor that often results in complacency, especially with respect to budgeting for preventative solutions. Coupled with laborious and costly monitoring of slopes over time, it is understandable that most decision support systems (DSS) that drive proactive transportation asset management (TAM) initiatives have not been implemented.

Current landslide inventory systems require significant time to develop and generally provide only basic information after a collapse has occurred. As such, they do not provide an understanding of how risk varies with time and location. A proactive, near-automated approach for the identification of slope instability offers the potential of reduce overall operation and repair costs while reducing economic consequences of interrupted transportation and commerce, while additionally enhancing public safety.

Remote sensing technology, such as lidar (light detection and ranging) laser scanning, shows promise for the rapid assessment of linearly distributed infrastructure systems, such as highways. Time-series lidar datasets enable a higher level of asset management confidence than current probabilistic studies based on landslide inventories.

The scope of this project includes the development of qualitative relative risk model for slope stability assessment using terrain models created from lidar data. In the second phase of the work, we will focus on quantitative time-series analysis using lidar data and integrating this information into the model developed in the first phase of research and into an agency's transportation asset/performance management program.

The major findings of this first phase of research include the following:

1. Static and mobile static terrestrial lidar systems improves the acquisition of repeatable data sets with a higher quality than mobile terrestrial lidar systems mounted on a vehicle traveling at highway speeds. This is because the static configuration on a tripod or tripod mounted on wagon requires the operator to consider optimal locations to collect scan data, including scans from multiple angles.
2. However, static platforms are much less efficient than mobile platforms and are not realistic to apply across an entire state (particularly a state as large as Alaska). An appropriate strategy would be to use mobile lidar along all sections of highway routinely complemented by static lidar acquisitions in areas that show the highest levels of slope degradation or have been identified previously as highly unstable.
3. The collection of high resolution imagery to render the lidar point cloud in real colors greatly assists in the interpretation of geologic features that cannot be identified solely based on lidar point cloud morphology. Thus a camera acquisition should be integrated with the lidar scanner. Moreover, care should be taken to ensure appropriate exposure thresholds are used on the acquired imagery.
4. There is always some amount of data "scrubbing" (data editing) with the lidar point cloud required. For example, transient features such as passing cars and people appear in the data. Certain atmospheric conditions create lidar artifacts

that should be removed. Perhaps most importantly, vegetation such as tufts of grass and tree saplings on a talus slope can create noise obscuring the slope characteristic behind the vegetation.

5. Most current automated ground filters are currently not well-suited to handle mobile (or static) lidar data because of high variability in point density and steep slopes. Hence, a significant amount of manual editing is required.

Finally, the qualitative risk analysis conducted in this first phase is precisely that – an approximation of landslide risk. True probabilistic risk analysis will require a quantitative analysis that can only be modeled with repeated collection of slope data using the lessons learned in this phase one project.

Chapter 2 Literature Review

Because this project encompasses multiple disciplines and bodies of knowledge, this chapter will focus on the most critical information from each of these bodies of knowledge most relevant to the project. This chapter will briefly introduce the concept of asset management in transportation, followed by an introduction to the emerging field of geotechnical asset management. Next, mobile LiDAR and its use in slope stability studies will be presented. This will be followed by a review of landslides and analysis procedures with risk assessment concepts.

2.1 Asset Management

Asset management is an important topic for transportation agencies, which has received much significant attention in recent years with ever increasing demand on the transportation system. A transportation asset management program must: 1) consider concurrently all relevant assets (bridge, pavement, slopes, walls, etc.) in a corridor or transportation system in order to make the best decisions and optimize lifecycle costs, and 2) aggregate condition indices among these disparate assets to get a holistic picture of the corridor/system. Effective asset management requires centralized data storage and integration of datasets across an entire organization.

Currently, these databases are often distributed into "silos" across many divisions within a transportation agency without a central link or repository (Singh et al. 2009, Olsen et al 2013a&b). For effective asset management, even at the most basic level of inventory and condition surveys, an agency needs to have overall system-wide objectives in place to effectively integrate assessment procedures for the wide variety of assets that the agency is responsible for. Potential performance goals can include safety, mobility, preservation, environmental, and/or economic criteria (Vessely, 2013). Ultimately, an effective asset management system is tied to evaluating and understanding the consequences of various degrees of action (ranging from inaction to complete reconstruction) so that resources can be optimally spent across the agency.

The use of geospatial technology has become more and more critical in obtaining rapid yet reliable information regarding an agency's assets. For example, Utah DOT has recently completed mobile laser scanning of all of their highways as part of their U-PLAN asset management system. Recent MAP 21 legislation strongly encourages additional usage of geospatial technologies for this purpose.

Within the context of asset management, a new area of geotechnical asset management has been evolving. Geotechnical Asset Management (GAM) can include the evaluation of landslides, unstable rock slopes (both natural and cut slopes), retaining walls, and embankments (Vessely 2013) which play a vital role in the functionality and safety of a highway corridor. A current difficulty in GAM is being able to appropriately track and monitor damage and deterioration of these assets. For other assets (concrete, asphalt, steel) reliable information on deterioration and performance exists from rigorous testing and empirical field implementation. However, given the high variability in soil type and physical properties, the performance of geotechnical assets can be difficult to quantify compared to other assets. Current limitations include 1) availability of resources to collect detailed, time series information along the entire transportation network, and 2) the ability to accurately measure degradation and determine thresholds of when failure is reached. New measurement technologies, including, but not limited to LiDAR, may be able to provide these missing links in GAM.

2.2 Mobile LiDAR

Three-dimensional laser scanning is a relatively new, versatile technology, and, as such, many applications of LiDAR have not been fully developed. Further, Mobile Laser Scan (MLS) systems have recently become available (in the last 5 years), which enable rapid, continuous data collection along highway corridors. For purposes of this discussion and report, to be consistent with common usage, Mobile LiDAR refers to a ground-based vehicle or platform to acquire the data and excludes airborne LiDAR, even though airborne LiDAR is also acquired kinematically.

Because of hardware and software costs, a steep learning curve, and other factors, MLS has yet to be widely adopted in the transportation sector for purposes related to Transportation Asset Management (TAM). Several DOTs currently use LiDAR technology on an occasional basis, but this use has been limited by the resources and time required for data processing and interpretation. Several DOTs currently use LiDAR technology on an occasional basis, but this use has been limited by the resources and time required for data processing and interpretation. However, DOTs such as Caltrans, Oregon DOT, and Utah DOT are integrating mobile LiDAR as a key component in their asset management programs.

For a detailed discussion of mobile LiDAR and relevant geospatial technologies in transportation applications, the reader is referred to the following resources:

- NCHRP Report 748: "Guidelines for the use of Mobile LiDAR in transportation applications." This comprehensive report provides a background on mobile LiDAR, detailed summary of applications based on a literature review and questionnaire, and guidelines for implementing and using mobile LiDAR for transportation.
- NCHRP Synthesis 446: "Use of advanced geospatial data tools, technologies, and information in Department of Transportation projects." This synthesis describes how DOTs are using various geospatial technologies, including mobile LiDAR.
- NCDOT Report: "Infrastructure Investment Protection with LIDAR," (Chang et al. 2012) provide individual summaries for a variety of applications of LiDAR usage (airborne, static, and mobile) for transportation applications. The report also presents results from a questionnaire to state DOTs as well as internal discussions within NC DOT to identify these applications and document lessons learned.
- AHMCT Report UCD-ARR-10-11-30-01: "Using Mobile Laser Scanning to Produce Digital Terrain Models of Pavement Surfaces" (Yen et al. 2010). This report evaluates the current capabilities and limitations of using mobile LIDAR to generate DTMs of pavement surfaces.
- AHMCT Report UCD-ARR-11-09-30-01: "LIDAR for data Efficiency" (Lasky et al. 2011). This report evaluates mobile LiDAR with respect to enhanced safety, improved efficiency, accuracy benefits, technical issues, and cost benefits with a focus on collection, processing, and storage of data.
- Missouri DOT Report TR10-007: "Light Detection and Ranging (LIDAR) Technology Evaluation" (Vincent and Ecker 2010). Provides an assessment of accuracy, cost, and feasibility comparing airborne, stationary, and mobile LiDAR.

This section will summarize much of the information presented in those documents.

2.2.1 Mobile LiDAR Technology

Mobile laser scan technology produces highly detailed 3D models of the terrain surface. Most mobile scan systems collect millions of points per second at accuracies (Root Mean Square (RMS)) on the order of 3-10 cm at spatial resolutions of 5-10 cm on the target surface. Data can typically be acquired up to 150 meters from the Mobile LiDAR Systems (MLS) vehicle. In addition to mapping, most scanners concurrently photograph the scene, assigning RGB color values to each scan point. Intensity values (i.e., the strength of the signal degradation) are also measured, providing additional information about the type of reflecting material (e.g., geology, vegetation cover etc.).

Mobile LiDAR systems can be configured in a variety of ways, depending on the general purpose of the system and requirements for a project. Several components are combined on a mobile scanner and data from these components are linked via precise time stamping. Yen et al. (2011) provide a comparison of many currently available mobile scan systems. Puente et al. [13] compare and contrast seven commercially produced MLS systems, and though there are many MLS mapping systems, most systems consist of similar basic components. Figure X shows the typical components and the remainder of this subsection will discuss the role of each component. Note that this text has been adapted from the NCHRP Report #768.

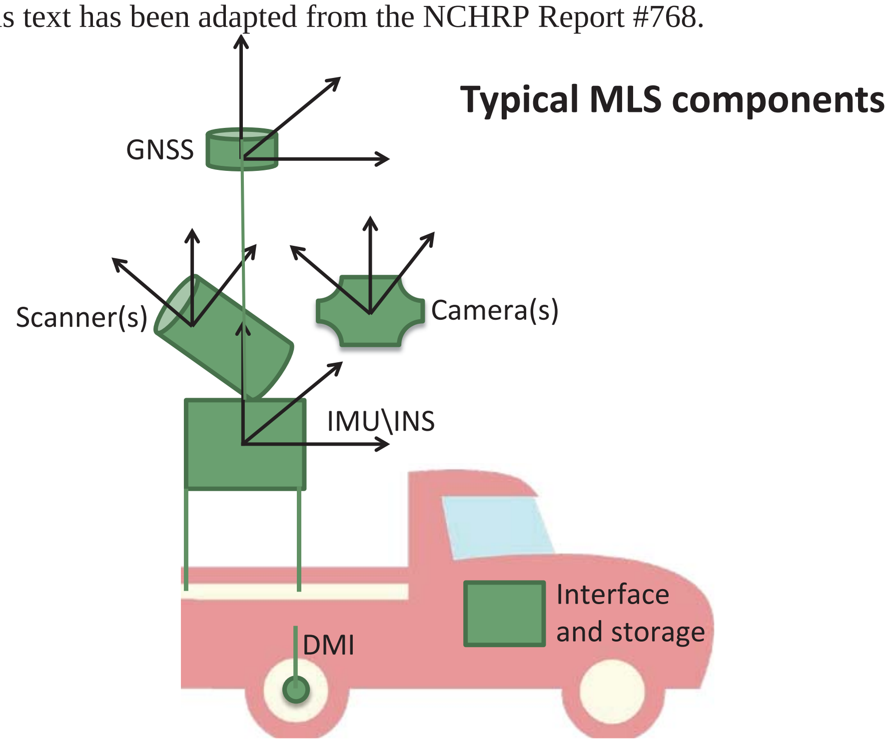

Figure 2.1 Components of a Mobile LIDAR system (from NCHRP Report 768)

- **Laser Scanners**

Laser scanners fire light pulses or emit continuous light waves at fixed angular increments to determine the range to objects relative to the scanner origin. Hence, native scan data consists of angles and ranges with timestamps. Although numerous commercially produced laser scanners are available for mobile LiDAR systems, there are two basic modes of operation in which scanners are used:

1. Static terrestrial LiDAR unit(s) that has been set to operate in a line scan mode. In this mode the scan head remains fixed (within context of the platform), and only internal mirror movement takes place to produce the scan lines. In order to collect a full 360° range of points multiple scanners are typically added to the system.
2. Rotating scan head (often tilted) with fixed laser(s) collecting data in a 360° planar sweep.

In either case, the movement of the vehicle coupled with the scanning plane of the sensor enables the system to collect data points across a wide window. Further, geometric orientation (i.e., look angle, distance to target) of the scanning heads relative to the surface of interest (e.g., horizontal ground surface vs. vertical building facades) plays a pivotal role in overall data quality because the incidence angle at which the laser strikes the surface causes variations in ranging accuracy. Most MLS will provide a direct view of adjacent cliffs that move upslope relative to a highway, but will not be able to capture the slope if it is downslope from the road.

Scanners also provide an intensity (a measure of return signal strength), which is an indication of target reflectivity and can be helpful to distinguish objects in the point cloud. However, intensity values vary by system characteristics, scanning geometry, multiple returns (e.g. the light\energy is split between multiple objects) and material type. Normalization procedures are being refined to correct for system characteristics and scanning geometry to enable consistent results between acquisitions (and systems), but this is still in the research and development stage. Hence, intensity values are useful in distinguishing between features within a dataset but should not be interpreted as absolute values and compared between datasets unless a normalization process has been performed and validated. For example, using the same system with a similar scanning geometry, one can distinguish between distinct, well-defined soil layers in the point cloud.

- **Global Navigation Satellite System (GNSS) Receivers**

The Global Navigation Satellite System (GNSS) is an expansion of the U.S. Global Positioning System (GPS) to include the Russian Glonass system, European Galileo (future), and Chinese Compass (future) satellite positioning systems. GNSS receivers provide three primary observations to the MLS: time, position, and velocity (speed and direction) measurements. Position and velocity information is provided to the logging computer(s) and also to the Inertial Measurement Unit (IMU, described below). An accurate GNSS receiver is vital to precisely geo-referencing the MLS point cloud, particularly over large distances. While real-time kinematic (RTK) GNSS processing (i.e., data are corrected for GNSS errors in real-time) is a possibility for MLS, data are often handled using post-processed kinematic (PPK) techniques to provide more flexibility during acquisition, and more reliability for final trajectory estimates. In either case, a base station needs to be close (within 5-10 miles) to the MLS for best results (Caltrans, 2011).

- **Inertial Measurement Units (IMU)**

The IMU performs two key functions: first, it provides orientation or attitude information (i.e., the roll, pitch and heading of vehicle), and second, it assists in position estimation, particularly when GNSS quality degrades. The GNSS system typically reports positioning information at rates of 1-10 Hz (i.e., one to ten measurements per second) while the IMU typically reports orientation information at a rate of 100-2000 Hz. The denser sampling by the IMU becomes increasingly important as the speed of the vehicle increases (e.g., a vehicle traveling at 60 MPH (97 km/h) will travel 88 ft. (27 m) in one second).

As GNSS positioning degrades, the IMU will begin to manage more of the positioning/orientation information using a filtering scheme (e.g., Kalman filter), which optimally combines all measurements of vehicle motion to minimize geo-location errors. Depending on the accuracy of the IMU (i.e., drift rate), the IMU may maintain accurate point cloud geo-referencing without the aid of GNSS positioning over extended periods of time.

- **Distance Measurement Indicators (DMI)**

A DMI is an encoder, normally placed on one of the wheels of the MLS vehicle, and measures tire rotation, which indirectly gives a measurement of distance travelled. A DMI is used in some MLS systems and serves to supplement GNSS and IMU with additional relative positioning information. The DMI is also incorporated with the GNSS and IMU information into the Kalman filtering scheme in order to provide forward velocity information for calculating the trajectory. The DMI may also be used as the primary triggering device for image capture points based on the distance travelled along the ground surface.

- **Digital Cameras**

Digital cameras are often incorporated into the MLS, providing a video log in addition to the scan data. With recent systems and software, each individually scanned point can be colored by a red, green, blue (RGB) value based on the acquired imagery. Different MLS will have varying camera arrangements ranging from front, rear, or side cameras to 360 degree panoramic cameras.

Geo-referenced images are mapped to the point cloud can enable users to create line work and annotations directly on the images that are linked to the point cloud rather than having to directly interface with the point cloud.

Photography is a passive sensing technology. This means that the quality of the image will vary depending on exposure, focus of the camera, and lighting conditions for the imaged scene.

- **Rigid Platform**

The rigid platform firmly attaches the laser scanners, GNSS receivers, IMU's, digital cameras, and any ancillary devices into one cohesive unit. Each component of the platform needs to be carefully calibrated so that the offsets between each component are well known and remain stable. The platform also permits the MLS to be transferred from vehicle-to-vehicle with much more ease than moving individual components.

- **Other Ancillary Devices**

Many other devices may be added to a MLS in order to provide additional value to the end user. Audio and video recording may be utilized for operators to make oral or visual notes as needed during data acquisition. A computing system must be incorporated to log the very large amounts of data acquired and to provide a user interface to command and control the MLS.

2.2.2 Applications

MLS systems have been utilized along navigable corridors for a wide variety of applications including earthwork quantities, slope stability, infrastructure analysis and inventory, pavement analysis, urban modeling, and railways. The recent NCHRP Mobile LIDAR Guidelines summarize a variety of applications for which mobile LiDAR has or could potentially be used. A recently compiled report for NCDOT (Chang et al. 2013) provide individual summaries of projects demonstrating a variety of applications of LiDAR usage (airborne, static, and mobile) for transportation applications. Figure 6 provides a graphical representation of many of the discussed applications. These applications are far from exhaustive, especially as new applications of MLS systems are being realized on a frequent basis.

The key concept is that the same MLS dataset can be used by multiple people in an organization. Hence, communication and data sharing can increase the value of data acquired and spread costs.

2.2.3 Application of LiDAR to slope stability analyses

Three-dimensional (3D) laser scanning has become increasingly effective for geotechnical and geologic analysis. Kayen et al. (2010) provide an overview discussion of a wide variety of geotechnical applications of 3D laser scanning including post-earthquake deformations, landslide analysis, liquefaction settlements, and trench volume calculations. TLS has also been used to undertake detailed geological assessments of several landslides, enabling improved understanding of the processes and mechanisms contributing to landslide movement (e.g., Jaboyedoff et al. 2010). Considerable work has also been undertaken in recent years to document the patterns of landslides and mechanisms for failure, particularly in forested environments where LiDAR provides detailed surface topography to delineate landslides that were previously undetectable. For example, Burns and Madin (2009) demonstrate a methodology using airborne LiDAR to map landslides in northwest Oregon, ultimately creating landslide hazard maps that could be used by local government for planning purposes. Similarly, Schulz (2005) presents approaches for landslide susceptibility estimation from airborne LiDAR data.

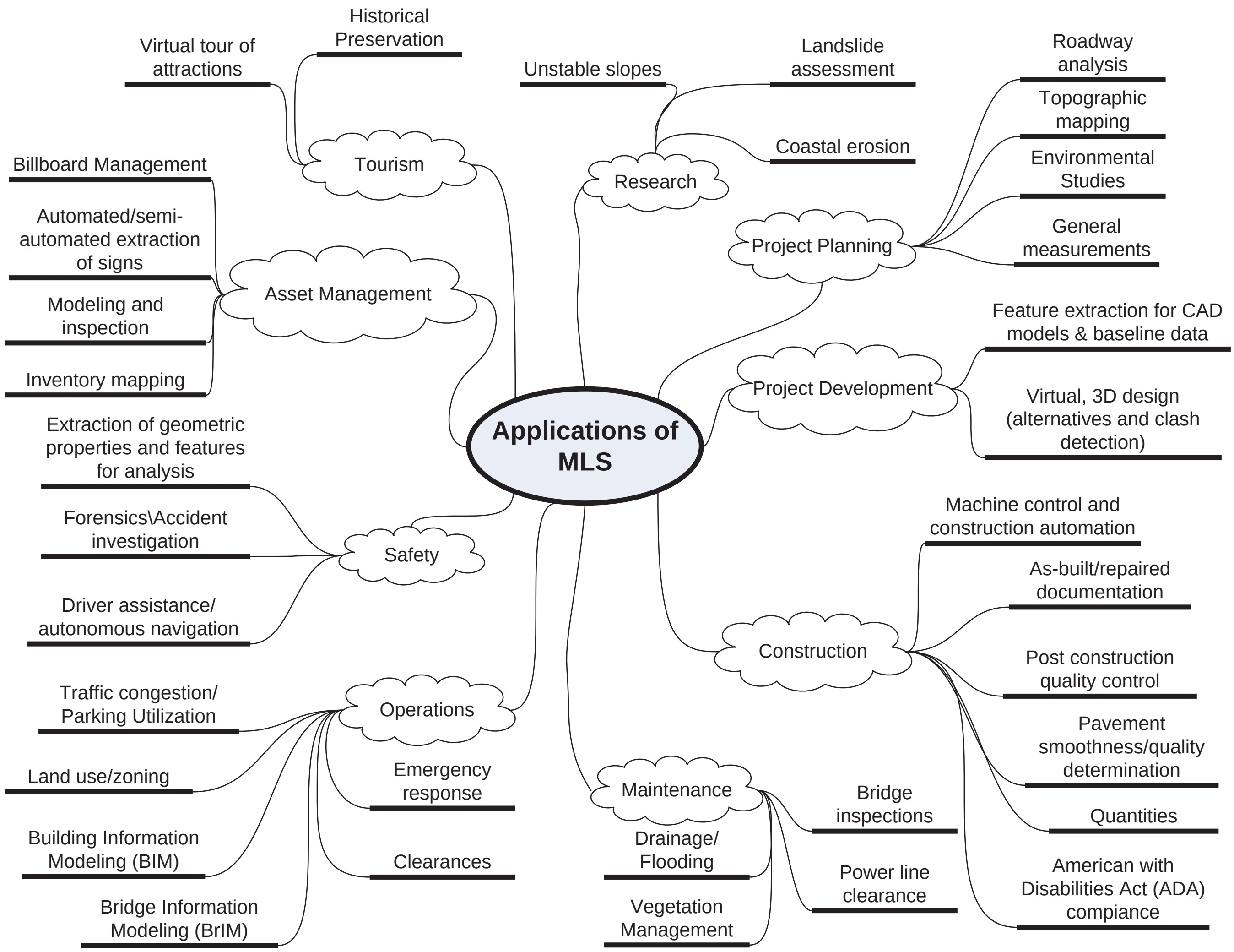

Figure 2.2 Graphical representation of common applications of MLS in transportation (from Olsen et al. (2013))

Terrestrial laser scanning (TLS) has been actively used for several transportation related slope assessments. A pooled fund study conducted recently evaluated the use of static LiDAR to map geotechnical conditions of unstable slopes, including rock mass characterization, surficial slope stability, rockfall analyses, and displacement monitoring. The report (soon to be released) provides an overview of ground-based LiDAR and processing software, discusses how LiDAR can be integrated into geotechnical studies, and includes case studies in the states of Arizona, California, Colorado (two sites), New Hampshire, New York, Pennsylvania, Tennessee, and Texas. The authors also discuss best practices and procedures for data acquisition to ensure it provides reliable data for geotechnical analyses. (Kemeny et al.).

Prior to the results of this pooled study, several other preliminary investigations were completed, often individually by state. Turner (2006) discuss processing procedures to use TLS to evaluate the stability of rocky slopes and how scan data can be integrated into geotechnical and geologic investigations. Kemeny and Turner (2008) evaluated the use of laser scanning for highway rock slope stability analysis and found that ground-based LiDAR offered several advantages compared to traditional techniques including safety, accuracy, access, and analysis speed. Kemeny et al. (2008) used LiDAR to evaluate several rockfall sites near highways in Utah and Colorado. These publications provide examples showing how information such as dip and strike can be extracted from "near-planar" features in LiDAR data to produce stereoplots to analyze slope stability.

Olsen et al. (2012) used TLS in conjunction with a geotechnical testing investigation to determine soil strength parameters to evaluate surficial slope failures occurring on fill embankment slopes for the US-20 Pioneer Mountain to Eddyville re-alignment project. Additional scans were acquired to determine the dipping plane of larger failures observed on cut slopes, such as that shown in Figure 3.

Su et al. [47] describe the use of LiDAR data for geotechnical monitoring of excavations, particularly in urban areas. In these urban excavations, real time monitoring of the excavation site as well as surrounding infrastructure is critical in maintaining integrity. Miller et al. [64] demonstrate the use of TLS in assessing the risk of slope instability, and provide two examples along transportation corridors. The authors note the challenge and safety issues that arise from setting up a stationary TLS instrument along the side of a busy transportation corridor Lato et al. (2009) demonstrate how rock fall hazards along transportation corridors can be monitored using MLS on both railway and roadway based systems. In both situations, MLS provided increased efficiency, safety, and the ability to investigate hazards. Lato et al. found that mobile LiDAR was advantageous compared to static LiDAR in coverage, acquisition rate, and corridor operation integration. Mobile LiDAR provided slope heights, angles, and profiles. Using a rail mounted mobile LiDAR system, 20 km of railway was acquired in 5 hours producing a 15 GB dataset with accuracies of 15 cm (absolute) and 3 cm (relative); The absolute accuracy was higher due to the railway being located in a deep canyon with poor GPS signal.

Figures 13 and 14 demonstrate similar use of LiDAR along unstable slopes in Oregon and Alaska.

Figure 2.3 Laser scan survey point cloud of the Johnson Creek landslide (June 2011).

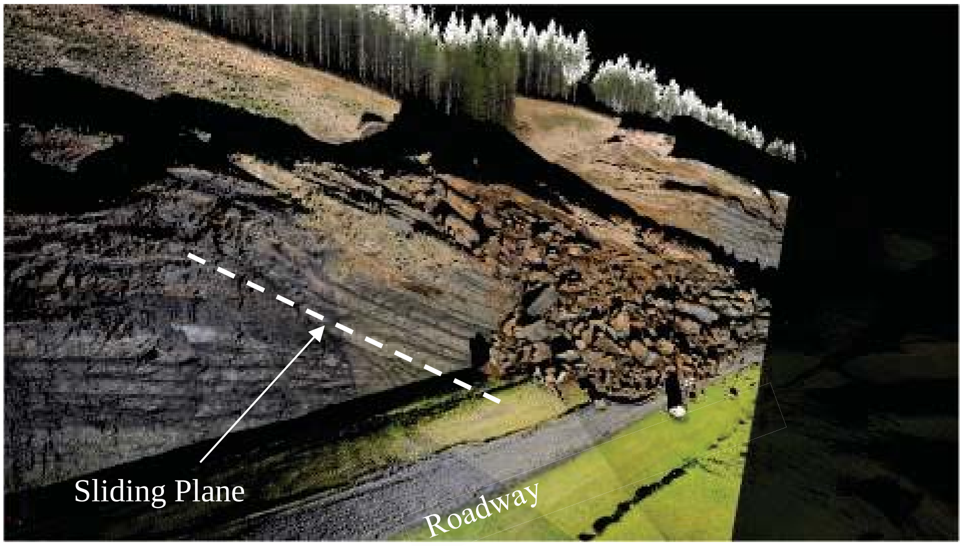

Figure 2.4 LiDAR scan of a deep slide on at the US20: Pioneer Mountain to Eddyville re-alignment project, which occurred in January, 2011

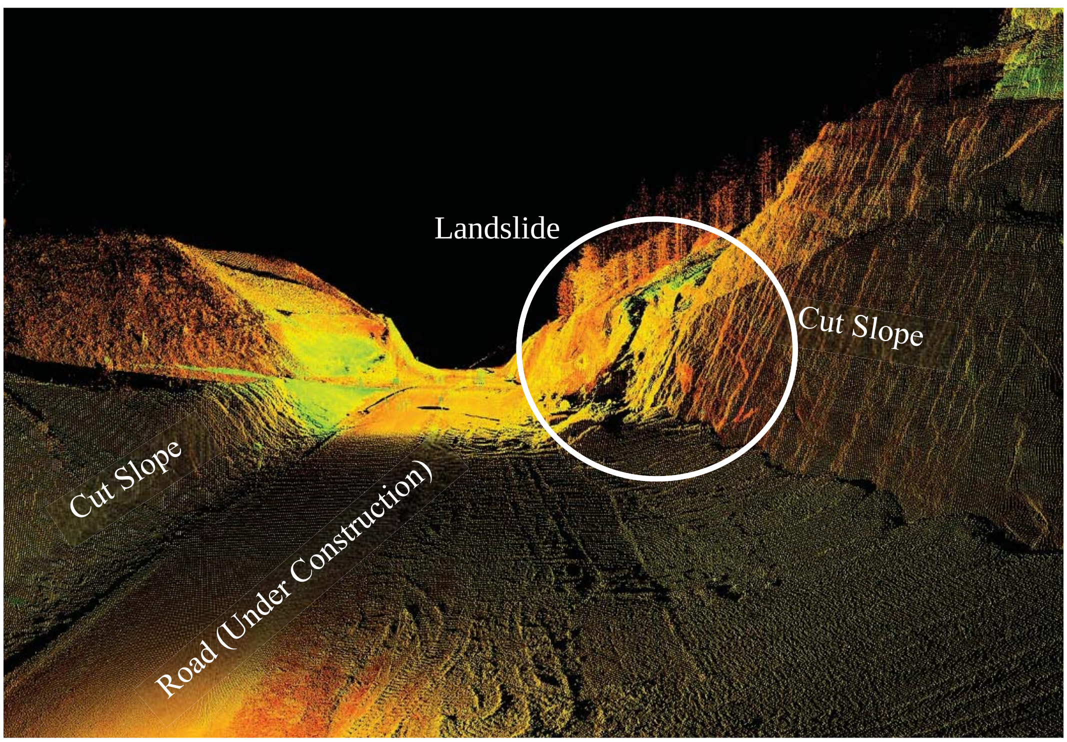

Figure 2.5 Point cloud of a rockfall on newly cut section for a highway (Courtesy of Oregon DOT).

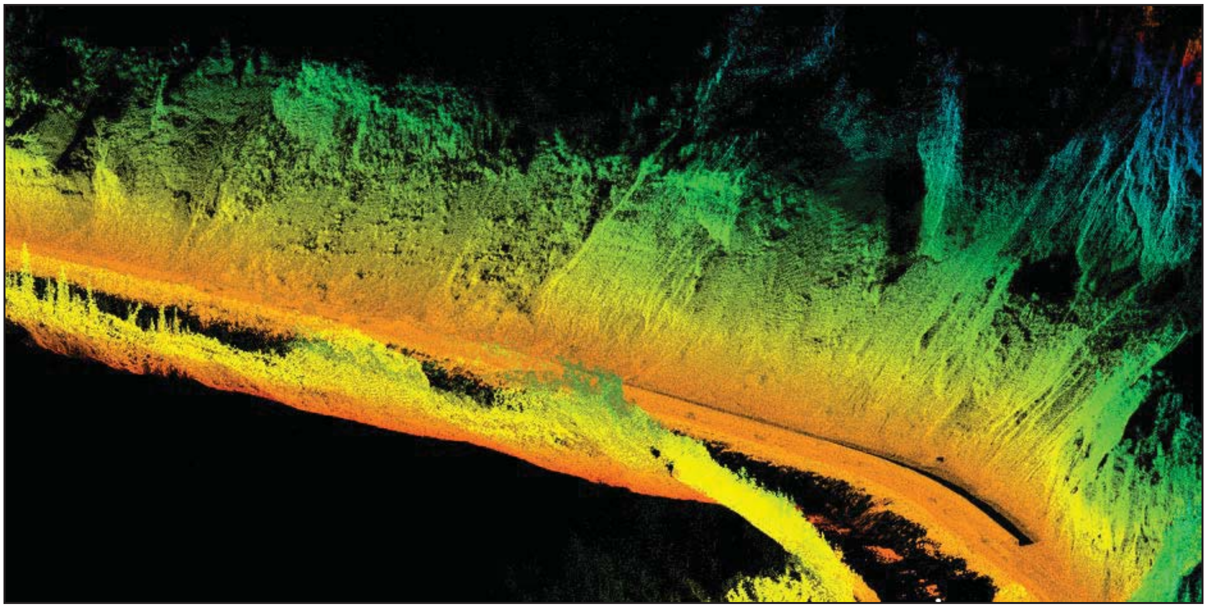

Figure 2.6 Point cloud for MLS data obtained for slope stability assessment on the Parks Highway near Denali National Park, Alaska.

Olsen et al. (2009) provide a methodology for acquiring TLS (stop and go) of long coastal cliff sections as well a parametric analysis to determine scan acquisition parameters such as scan spacing, distance from objects, and resolution. TLS provides many advantages over traditional methods of monitoring erosion, these advantages primarily coming from the density of the data points collected on the cliff faces. This allows for in-depth monitoring of accretion and excretion along the cliffs, as well as monitoring of large land mass movements. Figure 15 shows an example of such change analyses using surface models derived from LiDAR data. One of the challenges of working with TLS along these coastal sections is the necessity to time the ocean tides to prevent equipment and users from being submerged.

2.2.4 Change analysis\Volumetric computations

As in ALS and TLS, topographic mapping is an important application of MLS, including earthwork computations. Jaselskis et al. [36] performed a comparative study of total station and LiDAR based volume calculations from TLS. In this study, a 1.2 percent difference was calculated between the different methods, demonstrating that LiDAR can be a very efficient method of volumetric determination.

Vaaja et al. [37] researched the feasibility of using MLS to monitor topography and elevation changes along river corridors. The vehicles used in this study were a small, rigid hull, inflatable boat, and a handcart designed to be pulled along by an individual. Results showed that MLS provides accurate and precise change detection over the course of the study (one year), however, very careful control of systematic errors need to be accounted for. Vaaja et al. [37] note that the scanning field of view was often parallel to the topography, resulting in lower accuracy than scanning conducted more perpendicularly to the topography.

Recently, Olsen et al. (2012) developed an in-situ change detection program to enable immediate geo-referencing and comparison of new scan data to baseline surfaces to determine the distribution and quantity of change. Olsen et al. (2012) and Olsen (In Press) developed an algorithm that permits in-situ detection of changes that have occurred over a region of previously collected LiDAR data using static LiDAR. This allows field crews to immediately see where changes have taken place so that any additional measurements can be made at the site with no need for office processing of the point cloud. Although mobile LiDAR data is not often processed in real time, it can provide baseline information for such a framework.

Multi-temporal datasets acquired using scanning technology enable detailed change analyses through time. This helps geotechnical engineers understand the progressive patterns of failures and discern the influence of environmental conditions that lead to those failures. The figure below shows an example of change analysis for multiple surveys to evaluate erosion and landslide movement of the Johnson Creek landslide. Large movements (generally ~10 cm/year) of the highly-active Johnson Creek Landslide, located on the coast north of Newport, Oregon, are problematic for maintenance of U.S. Highway 101, where roadway deformation is visible at the north and south extents of the landslide. Site monitoring through several ground-based LiDAR scans of the bluff face since 2004 enable assessment of the spatial and temporal variability of erosion. Comparisons of each 3D scan survey enable quantification of erosion rates and surface deformation, which can be used to analyze the pattern and propagation of displacements that have taken place over the past seven years.

Young et al. (2010) compare ALS and TLS for quantifying sea cliff erosion. The TLS data enables detection of finer-scale changes, however coverage is limited. In many areas, MLS systems can rapidly obtain these finer-scale changes over a much larger region; this is important for coastal highways such as Highway 101 on the West Coast. Bitenc et al. [68] demonstrate that MLS can be used to monitor costal changes after large storm events, and allows greater flexibility over ALS.

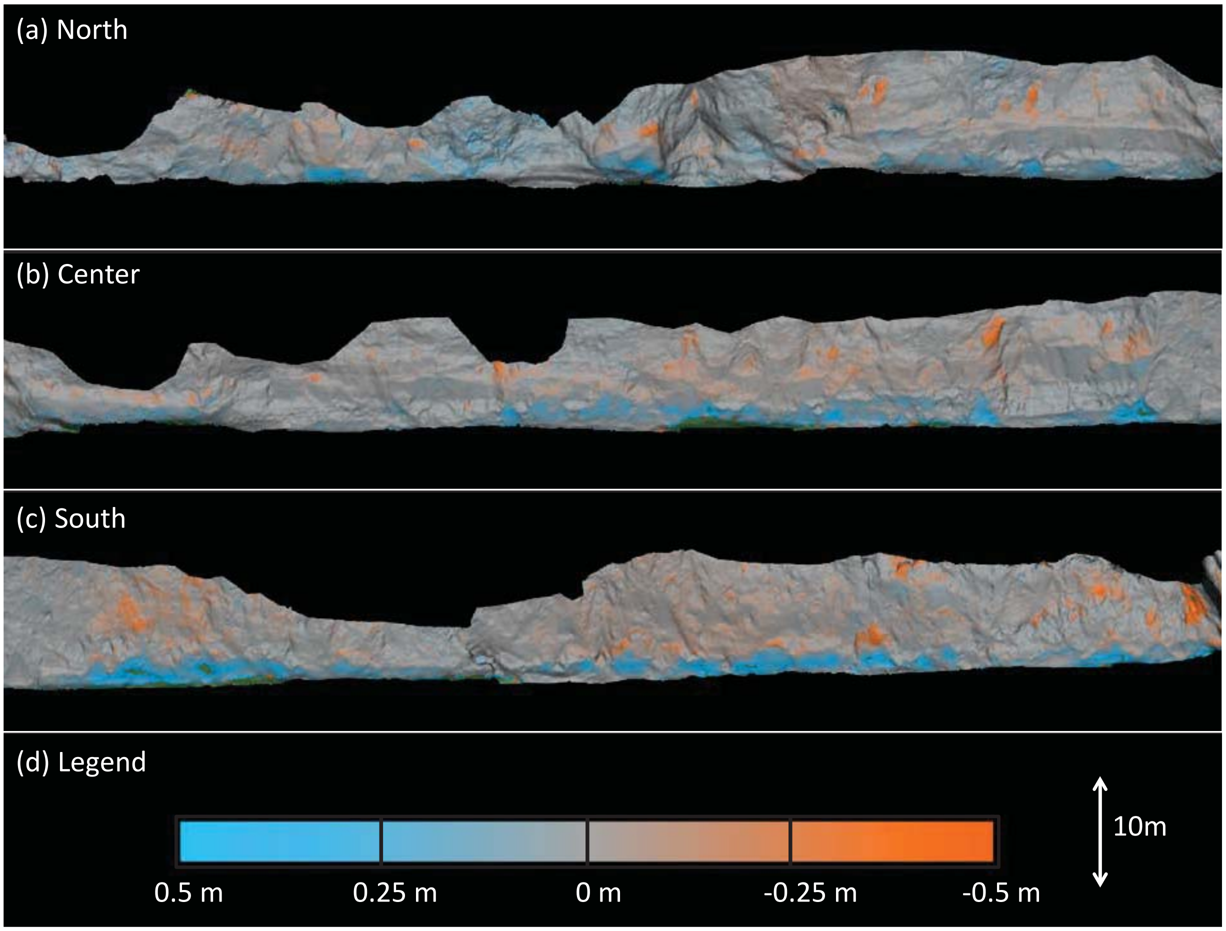

Figure 2.7 Change analysis between LiDAR surveys showing advance and retreat of the cliff face at the Johnson Creek Landslide, which continually damages Highway 101 on the Oregon Coast (courtesy of Jeremy Conner, OSU)

2.2.5 Extraction of surface metrics using LiDAR

One important topographical index that can be extracted from LiDAR is surface roughness. One should note that surface roughness is defined and calculated using a wide array of methods throughout the literature in various disciplines. This section will summarize some common approaches used for geologic features extracted from LiDAR data. A review of common techniques can be found in Berti et al. (2013) and Pollyea and Fairley (2011). Most of these approaches look at the variability of elevation, slope, or deviation from a plane or other datum within a window or cell. Some methods are calculated using the point cloud; others are calculated from a DEM or other surface model. Certain methods implement de-trending to determine roughness from the principal plane a feature is oriented rather than a fixed plane such as the XY plane. De-trending is critical when analyzing rock outcrops using terrestrial scan data. When considering surface roughness, it is important to evaluate the resolution that the data are available at as well as the scale of surface roughness of interest (e.g., micro scale on a surface vs. topography).

3. **Ordinary Least Squares (OLS)**: Fardin et al. (2004). This approach determines surface roughness as the residuals of an OLS fit of a point cloud to a plane.
4. **Orthogonal distance regression (ODR)**: Pollyea and Fairley (2011) developed an orthogonal distance regression approach to extract surface roughness from TLS data. This approach segments the point cloud into regular spaced, 3D grid cells, performs a localized plane fitting within each grid cell, and computes the orthogonal distances between the local plane and each point. The surface roughness for each grid cell is defined as the standard deviation of those orthogonal distances. The authors determined the ODR method to be an improvement over the OLS method because it was robust to outcrop orientation and OLS systematically overestimates surface roughness with decreasing grid size due to spatially correlated errors.
5. **Window searching algorithms**: Berti et al. (2013) describe various methods that search within windows for roughness. These metrics include: RMS height, RMS deviation, RMS slope, absolute slope, Std. Dev. Slope, Direction cosine eigenvalue, 3D semivariogram, wavelet lifting schemes, Discrete Fourier transforms, and continuous wavelet transforms. Through testing on simulated and natural surfaces, the authors concluded that although most techniques that de-trended the dataset performed similarly, simple approaches sometimes achieved improved results compared to the complex methods. The authors also investigated the influence of window sizes and conlude that the window size should be larger than wavelengths of interest for the natural surface.
6. **Standard Deviation of Slope**: Frankel and Dolan (2007) calculated surface roughness for a 1m pixel by using the standard deviation of slope within a 5m x 5m window of airborne LiDAR data. The DEM cell size was 1m. The authors found correlations between the age of an alluvial fan and surface roughness. Initially, the surface smooths with time until a threshold is reached and roughness increases rapidly due to surface runoff and tributary incision.

Hani et al. (2011) describe attributes of the ideal algorithm for evaluating surface roughness:

1. A local measure of the surface (e.g., pixel) rather than a global value
2. Simple to implement so that it is computationally efficient on a large dataset (e.g., LiDAR point cloud),
3. Provide an index that are invariant of rotation or translation and represent intrinsic surface properties,
4. Account for scale dependency characteristics of natural surfaces, and
5. Contain a physical or intuitive meaning.

Further, Brown and Hugenholz (2013) analyzed the influence various laser scan survey parameters on surface roughness measurements at centimeter scales. This study was completed in a controlled setting using artificial roughness elements placed across an asphalt surface. The study concluded that one should measure the size of roughness elements prior to scan acquisition so that an appropriate resolution can be selected. Point cloud registration errors between overlapping scans heavily influenced the roughness results.

2.2.6 Considerations

While LiDAR technology shows a significant amount of promise for slope stability assessment, much research needs to be completed in order to effectively and efficiently use LiDAR data to populate risk models for highway corridors. Currently LiDAR data requires a substantial amount of manual processing time to be developed into models usable in slope stability or other types of analyses. Automated algorithms for filtering and cleaning datasets are in their infancy, but are also rapidly improving. Additional challenges exist in coupling high resolution LiDAR data with sparse geologic and geotechnical information. Further, most slope stability models cannot take advantage of the high level of detail provided by a mobile LiDAR dataset. Developments of new slope stability techniques that can use high resolution 3D information will ultimately enable new insights across multiple scales of hazard analysis for slopes.

Further, much of the limited work that has been done using mobile LiDAR for slope stability has been in pilot projects, many of which have not yet been documented fully. As such, systematic procedures and guidelines have not been established for this application. This report documents the results of a MLS acquisition and analysis for slope stability, with the hopes that the information can aide in development of systematic procedures and guidelines for use of MLS for slope stability analyses along highway corridors.

2.2.7 Considerations of using mobile LiDAR for slope stability studies

The NCHRP guidelines provide several important considerations for using mobile LiDAR. This section will summarize relevant considerations from that document that are relevant to slope stability studies.

➢ **Visibility**

- While the MLS will capture objects within range and line of sight of the vehicle, non-visible objects will not be mapped. For example, the bottom of drainage ditches may be difficult to see in the MLS dataset.
- Scanning geometry (position and orientation of scanner with respect to object of interest) determines how well objects are captured. For example, specialized systems exist to capture very detailed pavement surface data, but are not configured to acquire data on surrounding features.

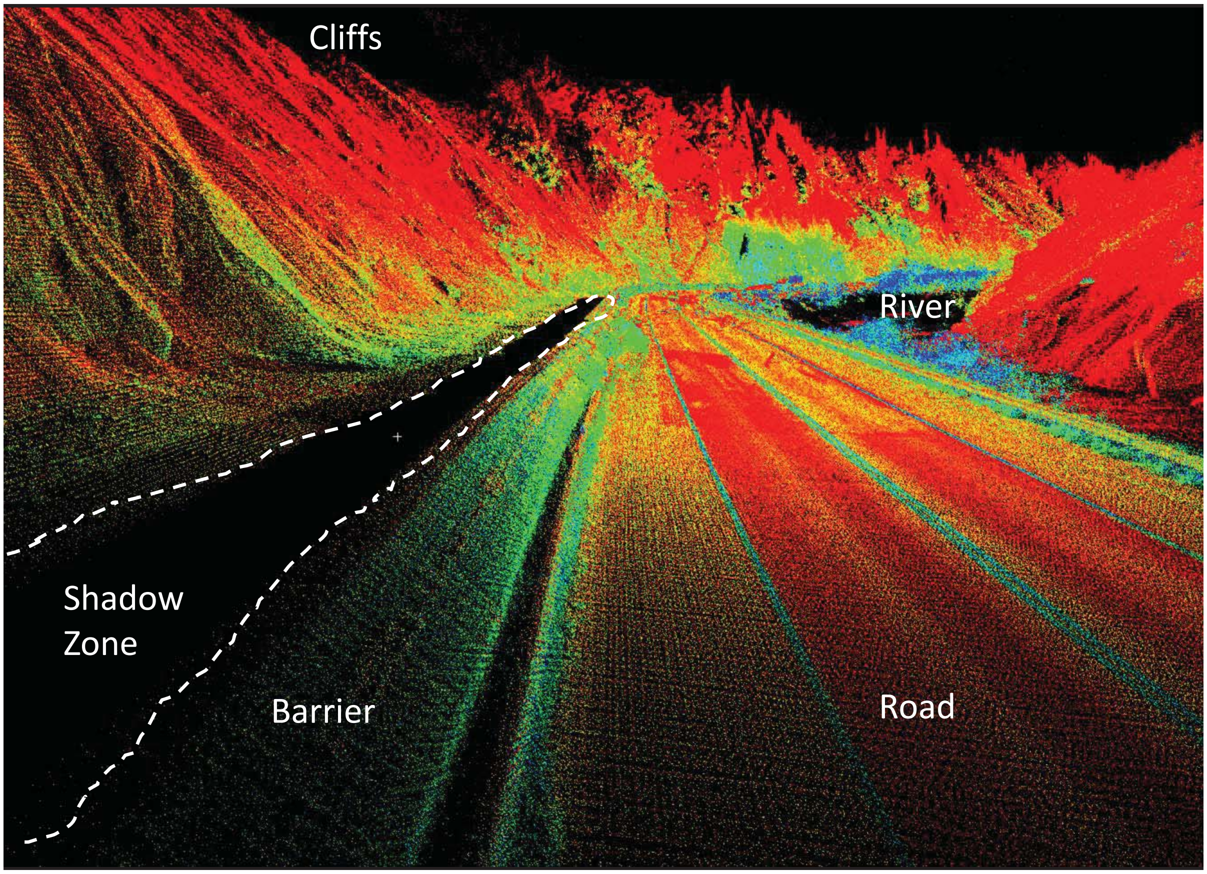

Figure 2.8 Example of shadowing effects from mobile LiDAR datasets. The point cloud is colored by intensity values.

➢ **Sensing capabilities and limitations**

- In addition to geometry, intensity values from MLS data can often be helpful to distinguish between distinct sediment types in outcrops.
- Highly reflective surfaces at close range can sometimes be problematic, creating saturation and blooming effects. Hence, reflective targets for monitoring or measurements should be used with caution and validated.
- Dark surfaces at long ranges are problematic for some scanners because they do not reflect light well.

- Wet pavements will generally yield poor scanning results, as do conditions where refraction is present, for example due to steam, precipitation, or heat rising from surfaces.
- MLS do not penetrate water.

➢ **Data quality**

- One can "see" noise in a point cloud because of the extremely high resolution; however, it is important to remember there is also be "noise" in other survey devices such as total station data that one cannot see because the points are spaced very far apart (several to 10's of meters).

➢ **Data processing**

- Many algorithms for data processing are in research and development. Hence, much processing is currently either semi-automatic or manual, depending on the application. Few completely automated procedures exist and those that do are in often specialized software packages. However, automated ground and other surface extraction algorithms generally work well for airborne LiDAR data. However, they can be problematic to implement on MLS datasets which have variable density and steep features of interest.
- The points in a point cloud natively do not have attributes other than XYZ coordinates and intensity values. RGB color from co-acquired imagery can be mapped to the point cloud through automatic processes. However, attributes such as what the point represents (i.e., point classification) are applied later through manual, semi-automatic, and/or automatic processing.

➢ **Monitoring**

- For slope stability, the accuracy and resolution required for MLS will depend on the speed at which the landslide is moving or the slope is eroding. In addition to spatial resolution, temporal resolution (i.e., how often repeat scans are conducted) should also be considered.
- Control points and objects near landslides can move and may not be reliable. A strength of mobile LiDAR is the amount of additional features that it captures in the point cloud. This enables one to readily capture data on stable objects to ensure the landslide movement is adequately detected and reliable.

➢ **Modeling**

- MLS is one of the fastest techniques to acquire data for a DTM of a road and surrounding area. It is very effective at acquiring detailed information on natural or cut rock slopes.
- Point cloud data is often subsampled or statistically filtered to create a DTM that will perform well in CAD or other engineering packages, which may not be designed for large datasets (e.g., file size, number of vertices).
- Breaklines will need to be extracted semi-automatically or manually, if desired.
- In many cases, TINS will actually be 2.5D datasets, not 3D. Hence, they will not model details on vertical surfaces (e.g., building, steep slope face) in the point cloud. This issue is particularly important when analyzing steep rock slopes and

slopes with overhanging features that are not properly resolved in 2.5D data. This issue will be discussed further in the methods section of this report.

- While CAD and GIS software offers support for point clouds and high resolution TIN models, many engineering analysis and design packages may not support the high density TINs created by LiDAR. A few potential solutions are:
- TINs with frequent, planar surfaces can often be significantly optimized to reduce the triangle count with minimal effects on the model accuracy using readily available software.
- Rather than use the point cloud to create the TINs, one can use extracted breaklines from the full point cloud and then use the breaklines with a subsampled version of point cloud (similar to a photogrammetric process).
- Dividing the overall dataset into individual tiles prior to creating the TIN may also help.
- However, some software may not be able to work with multiple tiles
- Higher densities will be needed to obtain ground points in areas of high vegetation. In some cases, the MLS system may not actually see the ground due to its oblique look angle. For example, downslope sections of slopes adjacent to roadways that are not visible from the roadway will not be captured.
- While for general basemap creation, natural terrain mapping will not require as high of resolution as pavement surfaces, particularly since sediment will erode or be deposited across natural terrain surfaces. However, in slope stability and erosion analyses, one will want to capture sufficient detail on the terrain to capture these effects.
- Analysis will likely need to be conducted in specialized 3D software.

➢ **Integration with other platforms**

- Many times MLS data will need to be supplemented by static or airborne scan data for slope stability studies. For example, when the road is on a slope, the MLS system will be able to acquire data on the uphill portion of the slope visible from the road (although coverage may be sparse near the top, depending on the slope and road geometry), but will not be able to acquire data on steep, downhill slopes that cannot be seen from the roadway.
- MLS can be used for small landslides and slopes, particularly when these slopes are steep. However, large landslides will require airborne LiDAR.

➢ **Logistics**

- In areas with heavy traffic, consider implementing a rolling "slowdown" to minimize vehicles blocking the scanner view. This will improve data completeness and reduce artifacts in the point cloud.

2.2.8 Comparison with Airborne Systems

Airborne and MLS share a number of similarities in the data processing workflow as both systems require the processing of positional data (e.g., GNSS, IMU) in tandem with LIDAR data. Per mission, airborne LiDAR can be significantly more costly than MLS if solely focused on highway corridors, and does not provide the same level of detail from the ground plane. On demand data capture can be provided by MLS, as well as capture of building facades and tunnels that are not available from airborne LiDAR [3,9]. However, airborne systems can cover larger portions of the terrain and are not limited to ground navigable terrain.

Key differences between mobile LiDAR (MLS) and airborne LiDAR (ALS) systems (Figure 5) include:

- Airborne scanning is performed looking down on the ground. Given the larger altitude of flight compared to terrain elevation variations (except for steep mountains) and limited swath width, point density tends to be more uniform than mobile LiDAR. Mobile LiDAR systems will collect data more densely close to the scanner path and less densely farther from the scanner path;
- The laser footprint on the ground is normally much larger for airborne LiDAR than for mobile or helicopter LiDAR. This leads to more horizontal positioning uncertainty with airborne LiDAR;

ALS generally will have a better (more orthogonal) view (i.e., look angle) of gently sloping or flat terrain (e.g., the pavement surface) compared to that of a mobile LiDAR system (depending on how the mobile laser scanner is oriented). This means that MLS systems will likely miss bottoms of steep ditches that cannot be seen from the roadway. However, mobile LiDAR systems will have a better view of steep terrain and sides of structures (e.g., Mechanically Stabilized Earth (MSE) walls, cliff slopes). Jersey barrier will block line of sight and create data gaps on the opposing side. Some projects may benefit from integrated mobile, static, and airborne data collection;

- MLS can capture surfaces underneath bridges and in tunnels;
- MLS is limited in collecting data within a short range (typically 100 m) of navigable roadways. Airborne platforms have more flexibility of where they can collect data;
- For MLS projects, accuracy requirements are the most significant factor relating to project cost. For ALS, acquisition costs generally control the overall project cost; and
- For MLS, the GNSS measurements are the major error source; whereas for ALS the IMU and laser foot print are the major error sources (except for low-flying helicopter LiDAR).

Similarities between the systems include:

- Both acquire data kinematically using similar hardware components (GNSS, IMU, and LiDAR).
- Both capture a point cloud.
- Both systems typically provide laser return intensity (return signal strength) information for each laser return.
- Each point is individually geo-referenced with both systems.
- While MLS can offer significantly improved horizontal accuracy due to look angle (<10 cm vs. ~50 cm for airborne), both systems can provide data with high vertical accuracy (<10 cm RMS).
- Both systems can simultaneously acquire imagery and scan data.

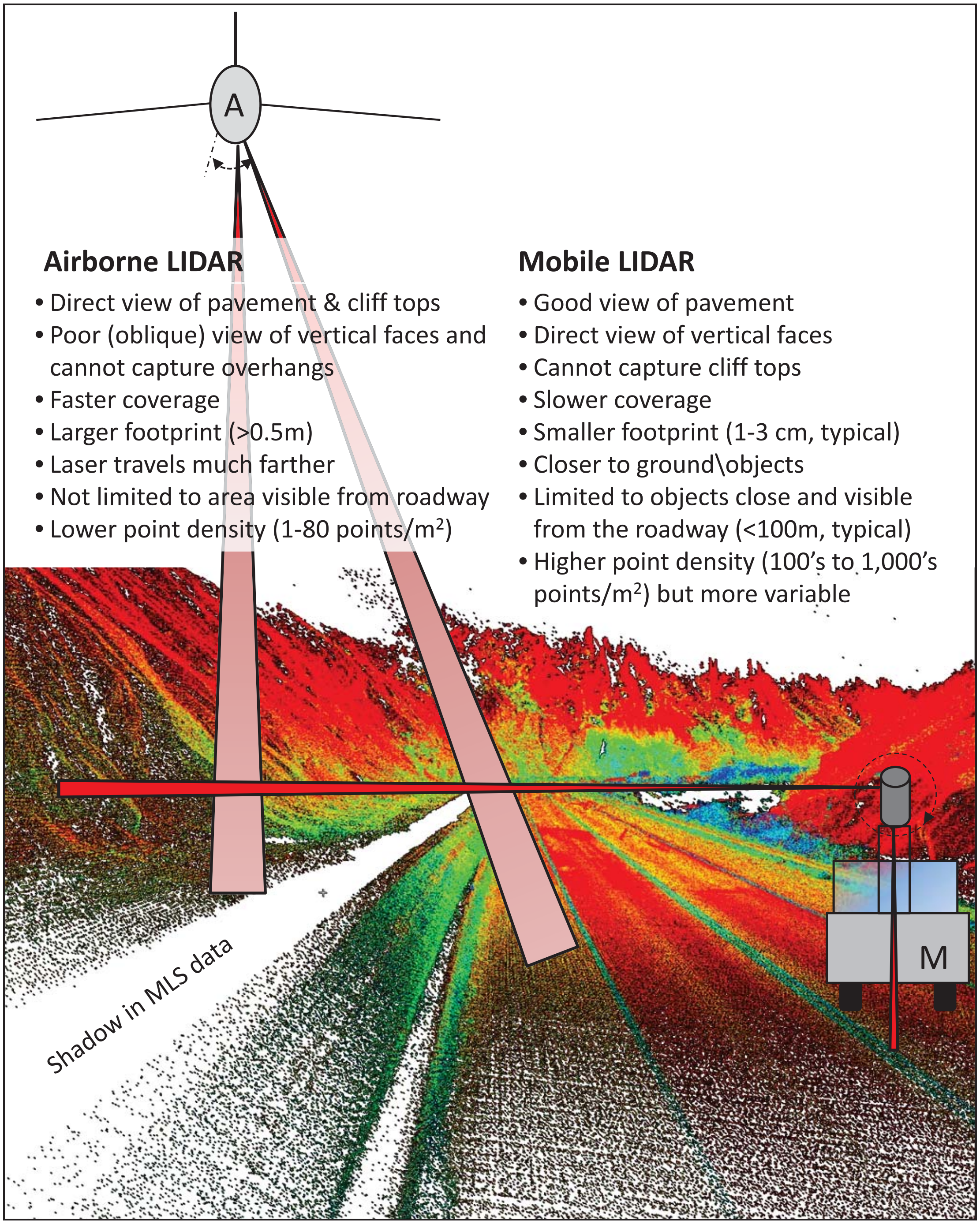

Figure 2.9 Comparison of airborne and mobile LiDAR systems.

2.2.9 Comparison with Static Scanning

Zampa and Conforti [31] provide data showing that MLS can be significantly more efficient than static TLS. For example, in 2007, an 80 km stretch of highway was scanned using TLS, and in 2008, 60 km of similar highway was scanned using MLS. The field time required to collect the TLS was 120 working days, while the MLS was able to capture all the data in three hours.

Static scanning can provide some advantages over MLS, especially flexibility. Static scanning provides more options for setup locations, including away from the road. Users can also determine the desired resolution at the single setup. This enables static scanning to obtain higher resolution on objects such as targets. Generally, higher accuracies and resolutions can be achieved since the platform is not moving.

2.2.10 Overall comparison

Based on findings from a literature review and questionnaire, Chang *et al*. [32] provide a chart to aid in selection of platforms for several applications with a discussion of generalized comparisons between mobile, airborne, and static terrestrial platforms based on several criteria:

1. Applicability—mobile systems can provide survey/engineering quality data faster than static scanning. Airborne systems (with the exception of low-flying helicopter) generally do not provide survey/engineering quality data.
2. Cost-effectiveness—despite a higher initial cost than static scanning, MLS received a higher cost-effective rating due to long-term benefits of reduced acquisition time.
3. Data collection productivity—Mobile and airborne LiDAR were both more productive than static scanning.
4. Ease-of use—because of the integration of multiple sensors and calibration of these sensors, MLS requires more training than static scanning. However, it requires less training than airborne because a pilot is not needed.
5. Level of detail—static scanning provided the highest level of detail.
6. Post-processing efficiency—airborne LiDAR had the best rating for post-processing efficiency and both static and mobile were given low ratings.
7. Safety—all platforms provided safety benefits compared to traditional forms of data acquisition; however, airborne received the highest rating due to limited traffic exposure.

2.2.11 Selection of mobile LiDAR for this project

Mobile LiDAR was selected for this slope stability project for several reasons.

1. Mobile LiDAR provides a direct view, orthogonal to steep rocky cliffs, which are difficult to capture using airborne platforms. Young et al. (2010) provides a comparison of ground-based LiDAR and airborne LiDAR. Figure X provides a comparison of advantages and disadvantages of the two platforms.
2. Mobile LiDAR can provide high accuracies (typically <5cm vertical, 95% confidence) and resolution (typically >400 points/m^2 on the cliff face)
3. Mobile LiDAR enables rapid coverage of a site compared to traditional, stationary surveying techniques. This will enable a DOT to acquire data across large sections of highways
4. The rich data in the point cloud can be used for a variety of other purposes than the primary intended purpose of the dataset.
5. Some difficulties with Mobile LiDAR are also worth noting:
6. Mobile LiDAR generates a wealth of data, which can be difficult to manage and currently requires a variety of specialized software to process.

7. Although imagery is co-acquired with laser data with most systems, a significant portion of available processing software does not directly link the images to the point cloud.
8. Specialized software is required to work with the point cloud data produced by Mobile LiDAR systems.
9. It is vital to understand that mobile LiDAR is an evolving, new technology. While the resolution of the data has been superior to many other techniques, capabilities and quality of data have been significantly improving over the last few years and will likely continue to improve with time as the technology and processing procedures improve. Hence, in a future study, one can likely expect improved results compared to what was possible during this study.

2.3 Slope Classification

A classification system is an organization of characteristics that aids in the comparison, quantification and/or categorization of a topic. Classification systems are common in many fields and allowing non-experts to better understand a topic and additionally, provide a concise description that is understood by all using the system. These systems also organize a subject into a useful pattern so that it can be better studied. (Singh 2011)

In rock-slope engineering, rock classification systems are commonly used to understand the slope processes and identify the factors contributing to instability. Rock slope classification systems help to simplify the complexity of slopes so that they can be distilled into simple units of understanding. These systems have been set up by experts in the field and allow users to evaluate the stability of slopes. Rock Classification systems communicate between different parties that are designing and constructing structures to allow for a common language and understanding. (Singh 2011)

Table 2.1 Rock Slope Classification Systems

System	Main Use
Rock Quality Designation (RQD) (Deere and Deere 1988)	Tunneling (used as parameter)
Rock Mass Rating (Bieniawski 1973)	Tunneling34
Rock Mass Quality Q-System (Barton, Lien and Lunde 1974)	Tunneling
Rock Mass Index (Palmstrom 1996)	Tunneling
Slope Mass Rating (Romana 1985)	Rock Slope Classification
Geologic Strength Index (Hoek and Brown 1997)	Rock Slope Classification/Tunneling
Rockfall Hazard Rating System (Pierson 1991)	Rock Slope Classification
Rock Slope Deterioration (Nicolson 2004)	Classify and mitigate erosional features in slopes

2.3.1 Slope classification systems used in this project

Table 1 summarizes several rock mass and/or slope classification systems that were considered for use in this project. To compare the systems, the attributes of each system were first categorized and assessed based on means of measurement, nature of the attribute (quantitative or qualitative), availability of required information, and use in practice (especially at the Alaska Dept. of Transportation). Based on this assessment, the Rockfall Hazard Rating System and Rock Slope Deterioration were judged to be the systems best suited for the project.

2.3.2 Rockfall Hazard Rating System (RHRS)

RHRS is commonly used by Departments of Transportations (DOTs) in rock slope assessment. Pierson first developed the system in 1984 for the Oregon DOT, and later in 1991 detailed the system in a design report. The original system covered 10 aspects rated 0 to 100 as summarized in Table 2 (Pierson, 1991). The scoring is exponentially scaled to more heavily weight issues that might result in failure. These aspects address elements of both hazard and risk for an overall risk assessment of roadways.

Table 2.2: RHRS Original System (Pierson 1991)

CATEGORY			RATING CRITERIA AND SCORE			
			3 POINTS	9 POINTS	27 POINTS	81 POINTS
SLOPE HEIGHT			25 FEET	50 FEET	75 FEET	100 FEET
DITCH EFFECTIVENESS			Good catchment	Moderate catchment	Limited catchment	No catchment
AVERAGE VEHICLE RISK			25% of the time	50% of the time	75% of the time	100% of the time
PERCENT OF DECISION SIGHT DISTANCE			Adequate sight distance, 100% of low design value	Moderate sight distance, 80% of low design value	Limited sight distance, 60% of low design value	Very limited sight distance 40% of low design value
ROADWAY WIDTH INCLUDING PAVED SHOULDERS			44 feet	36 feet	28 feet	20 feet
GEOLOGIC CHARACTER	CASE 1	STRUCTURAL CONDITION	Discontinuous joints, favorable orientation	Discontinuous joints, random orientation	Discontinuous joints, adverse orientation	Continuous joints, adverse orientation
		ROCK FRICTION	Rough, Irregular	Undulating	Planar	Clay infilling, or slickensided
	CASE 2	STRUCTURAL CONDITION	Few differential erosion features	Occasional erosion features	Many erosion features	Major erosion features
		DIFFERENCE IN EROSION RATES	Small difference	Moderate difference	Large difference	Extreme difference
BLOCK SIZE / VOLUME OF ROCKFALL/EVENT			1 Foot / 3 cubic yards	2 Feet / 6 cubic yards	3 Feet / 9 cubic yards	4 Feet / 12 cubic yards
CLIMATE AND PRESENCE OF WATER ON SLOPE			Low to moderate precipitation; no freezing periods; no water on slope	Moderate precipitation or short freezing periods or intermittent water on slope	High precipitation or long freezing periods or continual water on slope	High precipi-tation and long freezing periods or continual water on slope and long freezing periods
ROCKFALL HISTORY			Few falls	Occasional falls	Many falls	Constant falls

2.3.2.1 Uses in Department of Transportations (DOTs)

Since its publication, many DOTs have adapted the RHRS to their needs by adding, modifying or deleting parameters according to their state's needs and setting. A summary of several state-specific RHRS is found in Table 3. (Huang, 2009)

In the first version of the RHRS by Pierson (1991), hazard and risk pertaining to a slope were considered together. Later the system evolved such that the hazard and risk were considered separately. This is true of many of the state RHRS, including the system used for this project which is based on the Alaska DOT system modified from the Unstable Slope Management Program report (Huang et al 2009).

Table 2.3*:* Rockfall Hazard Slope Characteristics By Department of Transportation (Huang et al 2009)

Parameters	ODOT I	ODOT II	OHDOT	NYSDOT	UDOT	WSDOT	TDOT	MODOT	BCMoT
AADT	x	x	x	x	x	x	x	x	x
Accident History		x	x			x			
Annual Maintenance Frequency		x							
Average Vehicle Risk/HEF factor	x		x	x	x	x	x	x	x
Annual Maintenance Cost		x	x						
Backslope above Cut				x	x			x	
Benefit-Cost Ratio		x	x			x			x
Block Size/Volume	x			x	x		x	x	x
Detour Distance/Time			x			x			
Differential Erosion	x			x	x		x		x
Discontinuity Length	x								x
Discontinuity Orientation	x						x	x	x
Discontinuity Roughness	x			x	x		x	x	x
Discontinuity Weathering								x	
Ditch Dimensions	x			x	x		x	x	x
Ditch Effectiveness	x	x		x	x		x	x	x
Expect Damages/Fatalities			x			x			
Failure Zone length	x		x	x	x	x	x	x	
Freezing Period/Freeze-Thaw Cycle	x								x
Future Impact			x			x			
Highway Classification		x				x			
Impact to Road Structure		x	x			x			
Instability related to Rock	x	x		x	x	x		x	x
Instability related to Soil		x				x			
Instability related to Fill		x							
%Decision Sight Distance	x		x	x	x	x	x	x	x
Rate of Movement		x	x						
Roadway Width	x						x		x
Rockfall/Slide Frequency		x	x						
Rockfall/Slide History	x						x		x
Slope Height	x						x	x	x
Slope Angle			x	x	x	x		x	
Traffic Speed	x		x			x			x
Vertical and Horizontal Displacement			x						
Water on Surface	x			x	x	x	x	x	x

2.3.3.2 Selection of RHRS

A primary reason for this system being chosen was its common use by many states DOT. The system has a history of use by the Alaska DOT and it remains the basis of their current unstable slope management program.

2.3.3.3 Evaluation of the RHRS

The RHRS provides a standardized way to rate rock slopes in a manner that scores more critical items at a higher weight, thus emphasizing the possibility these factors may govern stability. The factors can be divided into risk—possibility of loss, and hazard—, the possibility of something happening that will cause loss. For the current phase of the research, hazard was focused on because it most closely related to the actual failure of slopes.

Some of the limitations of this system are that it is designed to be used by personal in the field. Therefore most of the attributes are assigned subjectivity. Another limitation is the system has categorical attributes that many of the slope sections in our study did not fit into very well (e.g., Structural Conditions for some sites did not specifically fit into one of the categories). This can be challenging especially when looking at the structural condition of the slope. Expert evaluation needs to be made for such situations.

2.3.4 Rockslope Deterioration Assessment (RDA)

The Rockslope Deterioration Assessment is used to look at the shallow weathering processes of rock slopes (Nicolson 2004). This system has three stages: classification, rock mass type and remediation. Only the first of these three stages (classification) was used for this project. The system has four main factors and nine adjustment factors that can be added to for special circumstances such as earthquake failure. Three of the main factors, Fracture Spacing, Fracture Aperture and Rock Strength use a graph to determine the RDA Rating as seen in figure 1. The fourth, Weathering uses subjective descriptions as seen in table 4. In Table 5 a list of the adjustment factors are listed.

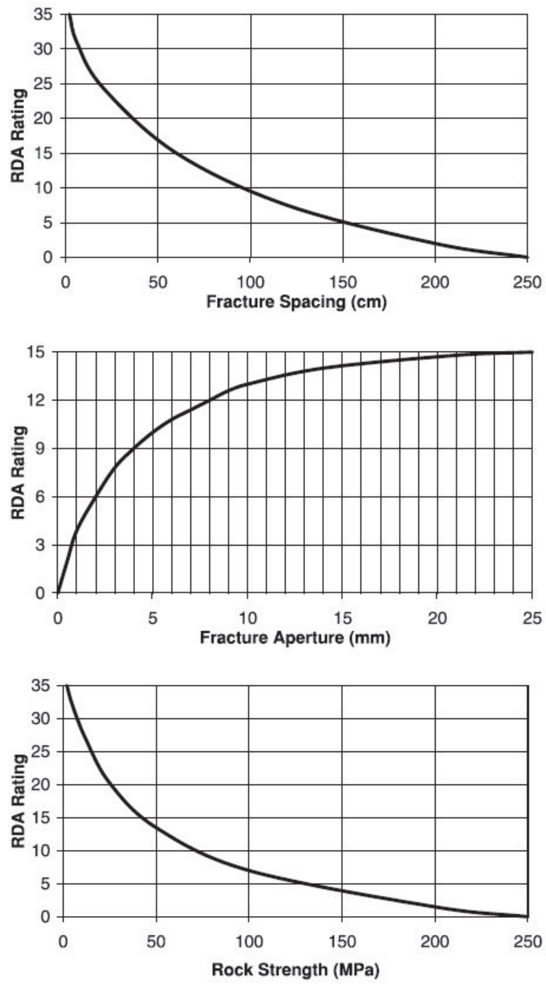

Figure 2.9 RDA Main Factors (Nicolson 2004)

Table 2.4: RDA Weathering (Nicolson 2004)

Grade	Material description	Rating
Fresh	Unchanged from original state.	0
Slightly weathered	Slightly discoloured; slight weakening.	5
Moderately weathered	Weakened in association with penetrative discolouration.	10
Highly weathered	Large pieces (eg NX drill core) cannot be broken by hand; does not readily slake when imersed.	14
Completely weathered	Considerably weakened; slakes readily; original texture retained.	15
Residual soil	No original fabric or texture remains (soil).	n/a

Table 2.5: RDA Adjustment factors (Nicolson 2004)

	Item
A1	Altitude and exposure
A2	Climatic conditions
B	Aspect
C	Ground & surface water runoff
D1	Static stress: Deep excavation
D2	Static stress: Surcharge
E	Dynamic stress
F	Excavation method
G	Stabilization measures
H1	Vegetation: Soil-like slopes
H2	Vegetation: Mature trees
H3	Vegetation: Rockslopes
J1	Slope geometry: Form
J2	Slope geometry: Roughness
K1	Rock structure: Mass v material
K2	Rock structure: Pattern
K3	Rock structure: Variability
K4	Rock structure: Favourability
L	Time since excavation
M1	Disturbance: Anthropogenic
M2	Disturbance: Undercutting

2.3.4.1 Selection for RDA

The RHRS System focused more on the structure of the slope while the RDA system examined erosional processes and was a good complement for the RHRS.

2.3.4.2 Uses of RDA

RDA is a limited classification system and is used to assess the progressive breakdown of rock slopes. This system is not designed to be an inventory system, but to look at individual slopes and assess them for potential failure risks.

2.3.4.3 Analysis of the RDA

The RDA system complements the RHRS system and fills the void that is missing with regard to the erosional processes that are a major factor in this project. Most of the categories are easily measured and there is flexibility in the system to fit the need of the assessment. This system though has not been used on large scale and is not intended to be up scaled for inventory proposes. This makes some of the implementation difficult and attributes need to be slightly modified to meet our needs.

2.4 Asset Management and Risk

Asset Management

The goal of any infrastructure asset management program is to assist in maintaining a desired level of safety and service with costs optimized over the long-term. Thus, in the case of transportation assets in Alaska, such a formal program can provide for the strategic, systematic, and coordinated programming and planning of expenditures for the design, construction, maintenance, operation, preservation and in-service evaluation of all facets of the state's transportation assets throughout their life cycle. Transportation Asset Management (TAM) provides an objective means for identifying construction, maintenance, repair and replacement needs that will provide the greatest long-term benefit to the system as a whole. Such an approach focuses on business and engineering practices for resource allocation and utilization, with the goal of better decision-making based on quality information and well-defined objectives.

TAM is a rational business model that couples business and engineering processes to performance of the transportation system. In so doing, it promotes safety, efficiency, expansion and longevity of the State transportation system. The methodology includes the systematic identification of objectives, development of alternative solutions, and analysis of their life-cycle cost impacts. The objectivity inherent in the TAM approach strengthens the case for allocation of funding and optimizes benefits derived from that funding. (TRB 2009)

An asset management program provides objective information and decision-making tools in a format useful to those who, ultimately, must use this information in conjunction with other considerations to decide how funding will be allocated to assets and projects. Thus, TAM provides Alaska DOT&PF with guidance and decision-making tools for wisely investing public funds in ways that minimize long-term costs while maintaining appropriate levels of service. The improved decision-making applies to designing, constructing, operating, expanding, and preserving Alaska's transportation system today and in the future.

Risk

There are numerous ways to define risk. This is due largely to fact that the way people define risk is contextual in nature. Definitions of risk tend to be influenced by philosophical, psychological and sociological factors (Kelman 2003). However, regardless of context, risk must be well defined to make rational decisions concerning it.

In terms of managing an inventory of engineered facilities, it is desirable to have a method for quantitatively defining risk. Ideally, the method would resolve risk to a standardized measure. *Probabilistic Risk Assessment* (PRA) is a comprehensive and systematic method to evaluate risk associated with complex engineered systems. This method characterizes risk by combining two concepts (Bedford and Cooke 2001):

- The severity of a possible event(s) – consequences of the event(s)
- The frequency or likelihood that the event(s) will occur – likelihood of the event(s)

If both of these metrics are quantified, then it will be possible to assign a numerical value to risk – providing a means of comparing alternatives based on their associated risk. PRA theory makes use of this principle when comparing alternatives for the design of engineered systems.

Kaplan and Garrick (1981) present a formalized approach for quantifying risk that includes a *Risk-curve*. This method combines severity and likelihood of a consequence by plotting all possible [failure] likelihood/consequence scenarios using cumulative probability (ordinate) and increasing severity (abscissa); resulting in the risk curve. In this reference, the risk-curve represents a quantified measure of risk. This reference is cited prominently by (Bedford and Cooke 2001).

(Rausand and Høyland, 2004) express a position that risk is a function of the potential consequence and frequency [probability] of a critical event.

Other sources on this topic indicate that risk may be quantified as the product of uncertainty and loss associated with a particular [damaging] event (Frankel 1988); (Moddares, Kaminski and Krivtsov 1999).

In terms of landslides, available literature tends to table the concept of risk to include <u>probability of a landslide</u>, <u>exposure to the landslide</u>, <u>vulnerability to a landslide</u> and <u>value of elements at risk</u> from a landslide (Lee and Jones 2004). In this sense, vulnerability is defined as the proportion of the value likely to be negatively affected by a landslide. Exposure is the total value likely to be present during a landslide event. A resulting equation for risk may be written as (after Lee and Jones 2004):

$$R = P\left(H_i\right) \times \left[C \times V \times E\right] \qquad (0.0.1)$$

Where: R = Risk value or score

$P\left(H_i\right)$ = Probability of a landslide of magnitude, i

C = total value of the elements at risk

V = vulnerability of the elements to a landslide

E = the total value of the elements likely to be present during a landslide

Chapter 3 Study Site

The study area was determined among geotechnical engineers at the Alaska Department of Transportation and Public Facilities (AKDOT&PF) and researchers at the Pacific Northwest Transportation Consortium (PacTrans). PacTrans researchers include faculty from the University of Alaska, University of Washington, and Oregon State University.

3.1 Study Sites

Study sites of interest are locations with slopes along transportation corridors that would be suitable for formulating a proactive method of slope stability analysis. The two sites identified are Glitter Gulch and Long Lake.

The study areas of the two sites in Alaska are shown on Figure 3.1. The first site, referred to as "Glitter Gulch," is located between mileposts 239 and 247 on the Parks Highway, Alaska route 3. The second site, "Long Lake," is situated between mileposts 78 to 89 on the Glenn Highway, Alaska route 1.

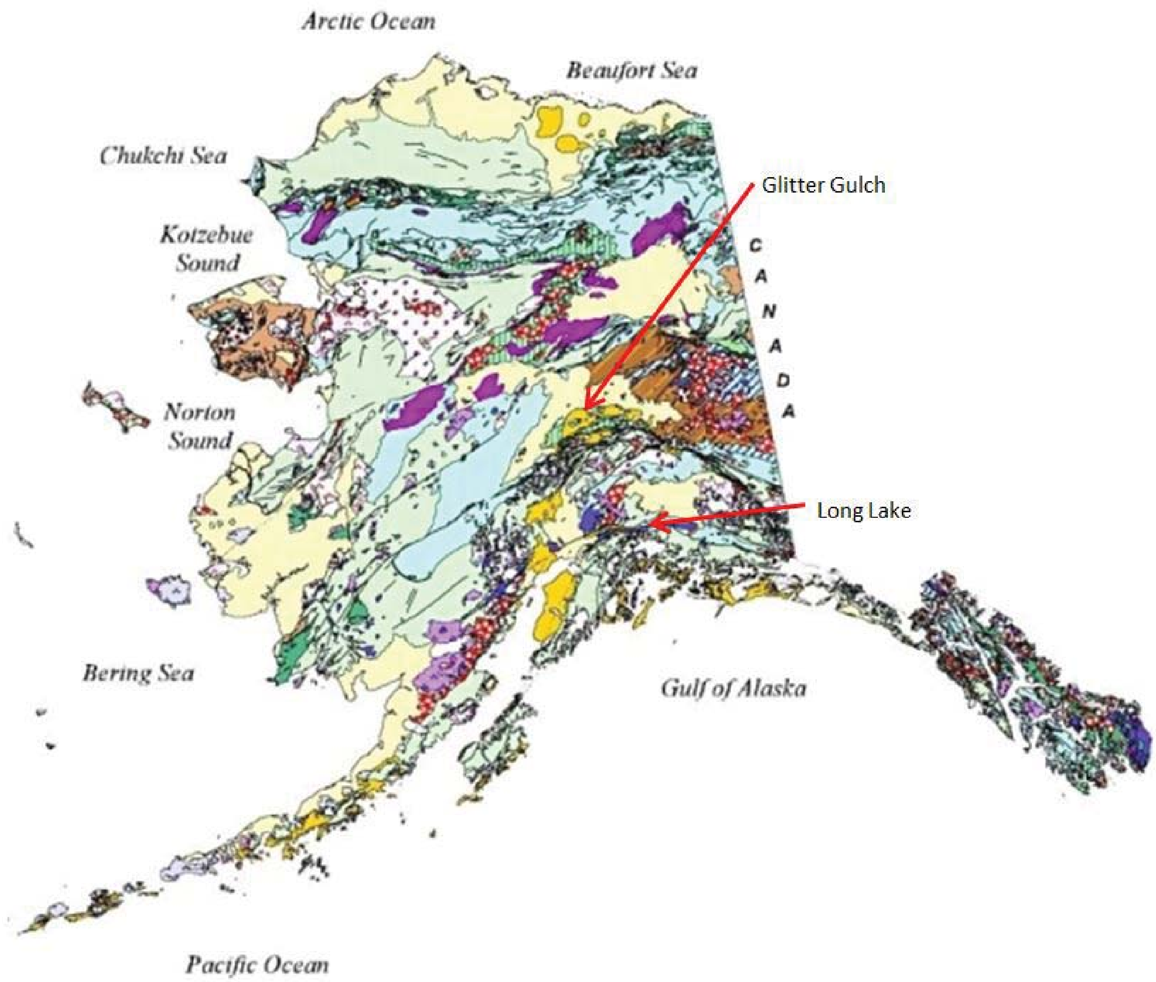

Figure 3.1 A generalized geology of Alaska (Alaska Department of Resources)

3.2 Geologic Setting

Alaska largely consists of a piecemeal mixture of accreted terranes as shown in Figure 3.1. These terranes are the product of subduction, whereby the pacific plate acted as a conveyer belt of material bringing portions of distinctly different rock that has become bound together by faults (Thornberry-Ehrlich 2010). Figure 3.2 is a north-south cross section of Alaska that shows the various terranes accreted over geologic time. The collision of these terrane with the existing land mass has caused the uplift of mountains (i.e., Orogeny), volcanic activity, and seismicity that are associated with Alaska today.

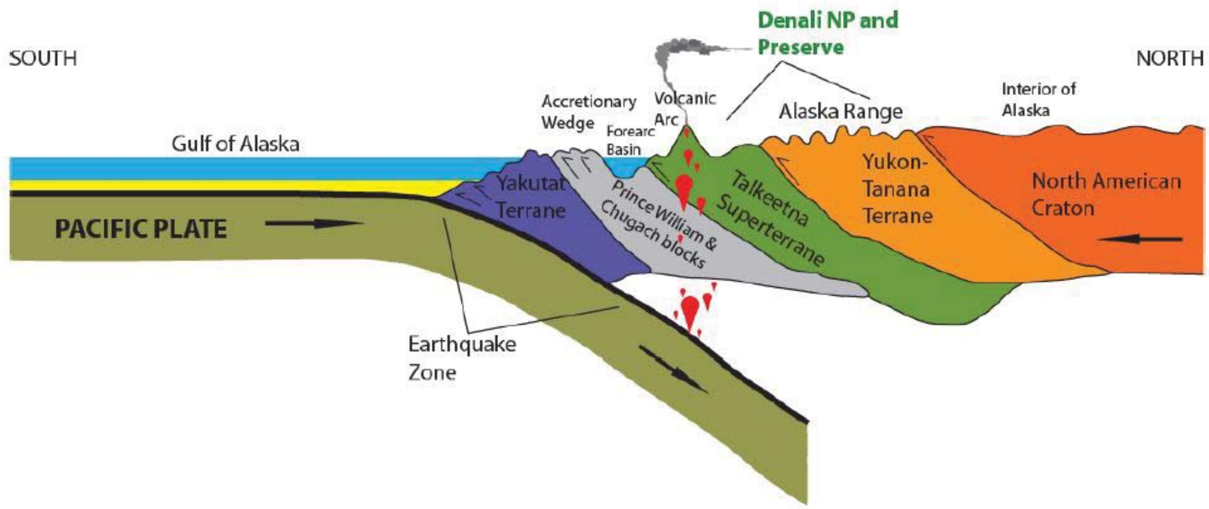

Figure 3.2 Alaska Terranes (Thornberry-Ehrlich 2010)

3.3.1 Geology of Glitter Gulch

Glitter Gulch is located within the Yukon-Tanana Terrane, which is the oldest terrane that has been transplanted to Alaska. This terrane is part of what is now known as the Alaska Range, a chain of mountains that extends east to west along the south of Alaska creating a drainage divide between the Cook Inlet and the Yukon lowlands (Thornberry-Ehrlich 2010). The Alaska Range is also faulted by the Denali fault which runs approximately 20 miles (30 km) to the south of the study area and does not directly affect Glitter Gulch. There are glacial deposits that are visible on the west side of Nenana River near the railroad tracks, however, there are no glacial deposits near the slopes forming the focus of this study (Hults 2013).

The main type of rock found within the Glitter Gulch study area is a rock is known as Birch Creek Schist or Healy Schist that Connor (1988) describes as “metamorphic rocks, muscovite-quartz schist, micaceous quartz and lesser amounts of graphitic schist.” Wahrhaftig (1958) notes that Birch Creek schist is inherently weak because of its "ease of separation along planes of foliation, produced by tiny, oriented mica flakes." This rock also includes cross joints, which run near vertical and may locally abut basalt dikes. Figure 4.3 is a geologic map of the area that shows volcanic dikes (Tvim, Tvif) within the Healy schist (PzpCp). The volcanic rock can be clearly seen as the darker rock in Figure 4.4, with a lighter Healy schist layer below.

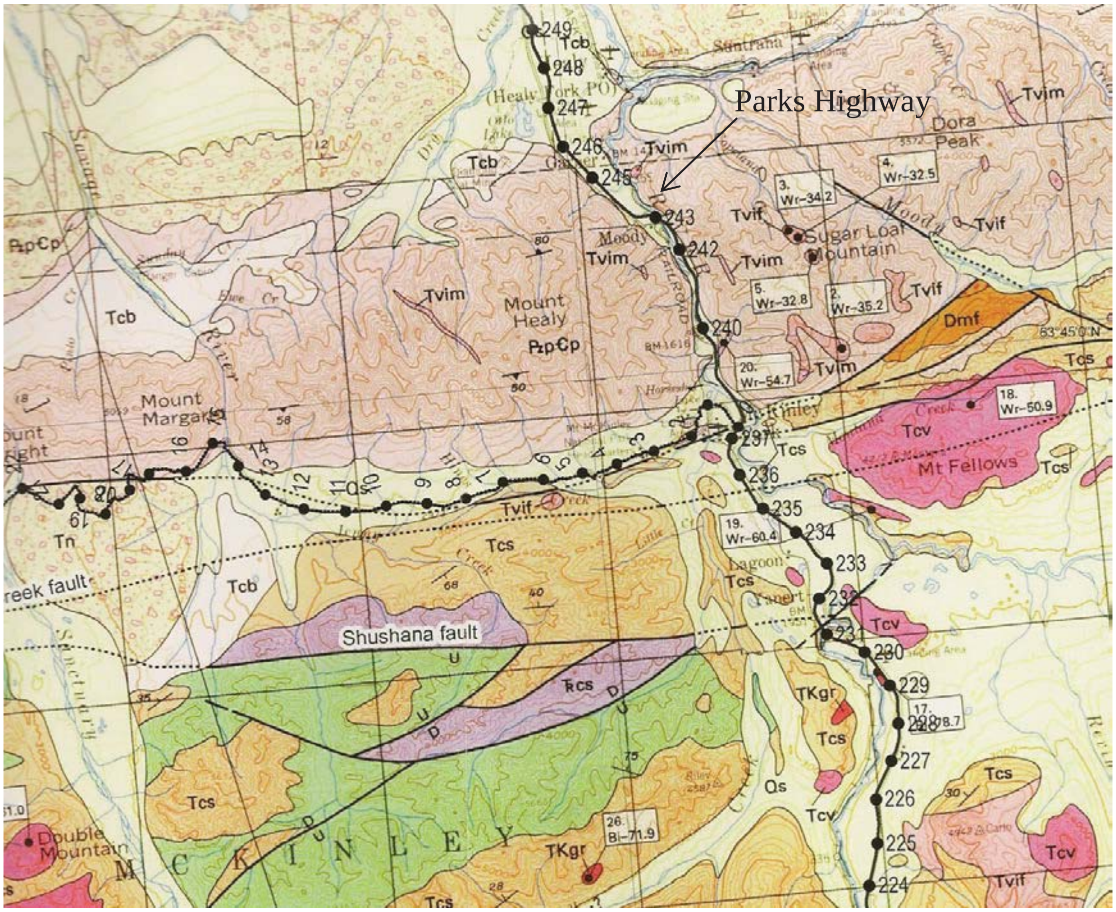

Figure 3.3 Glitter Gulch area geology (Hults, Capps and Brease 2013)


Figure 3.4 Example of Glitter Gulch rock slopes

3.3.2 Geology of Long Lake

The Long Lake site, which also lies within a region of accreted terrane, primarily consists of sedimentary rocks of the Matanuska and Chickaloon Formations. As shown in Figure 3.4, The Matanuska Formation, is a marine sedimentary deposit formed during the orogenic rise of the Talkeetna Mountains. The Chickaloon Formation (Figure 3.5 b and c) was deposited as propagating alluvial fans on top of the Matanuska Formation that formed as the Talkeetna Mountains were uplifted and sequentially eroded. (Belowich 2006) The Castle Mountain Fault runs parallel about 3 miles (5 km) north of the Long Lake; there is no evidence that it is active and affects the study area. The highway follows the glacial cut into the Chickaloon Formation; however, no other glacial evidence may be found in the area. (Trop 2006)

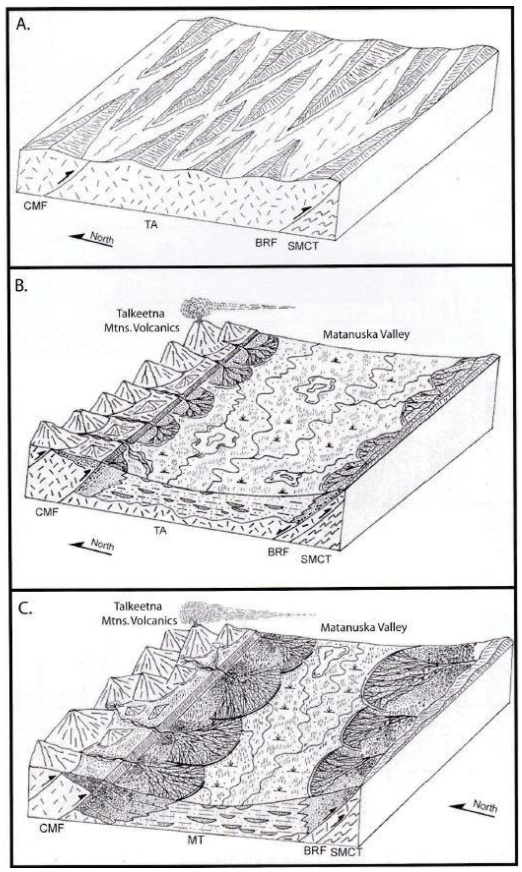

Figure 3.5 The building of the Long Lake area (Trop 2006)

The Matanuska Formation is exposed in road cuts and rock outcrops around milepost 85 and largely consists of dark mudstones. The Chickaloon Formation is mainly carbonaceous siltstone, coal and sandstone and extends across the Long Lake site (Trop 2006). Mafic sill intrusions are located throughout the Matanuska and Chickaloon Formations. Figure 3.6 presents a generalized cross section of the Long Lake region showing the Matanuka formation (Km) below the Chickaloon formation (Tc) near the Castle Mountain Fault (CMF). Figure 3.7 depicts the general geology of the Long Lake region, with the dotted line indicating the location of the Glenn Highway.

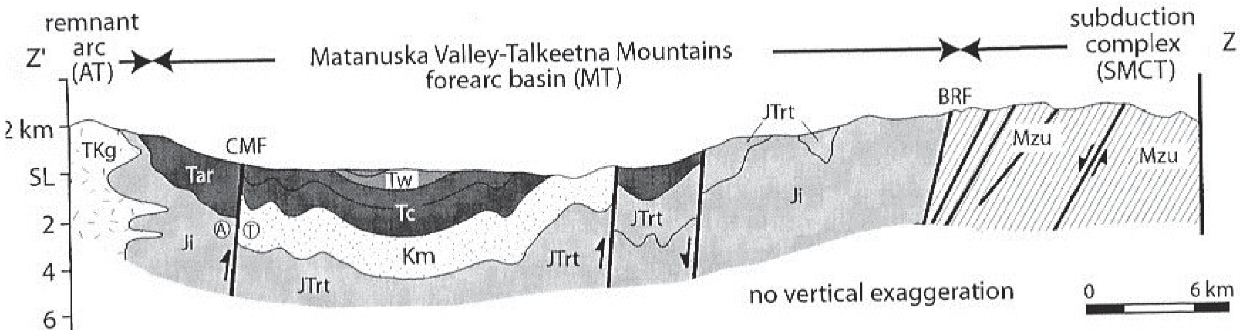

Figure 3.6 Cross section of the Matanuska Valley-Talkeetna Mountains forearc basin (Trop and Plawman, 2006)

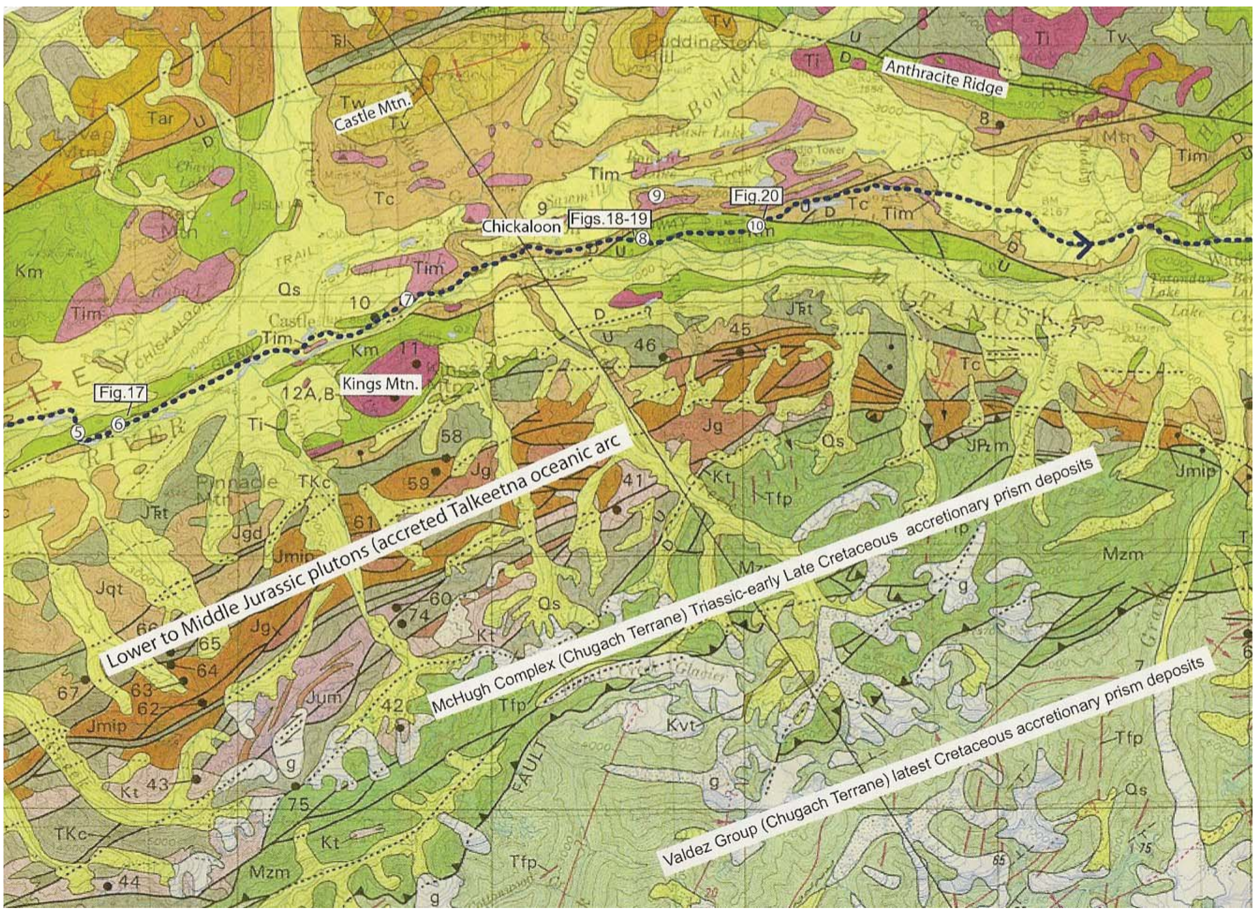

Figure 3.7 General geology of the Long Lake area (Trop and Plawman, 2006)

3. 4 Climate of the Study Region

Table 3.1 summarizes the climate of the Glitter Gulch and Long Lake regions. Weather station "*Healy 2 NW*" is located near Glitter Gulch, while the "Matanuska" station is located near Long Lake. Note that the local climate varies between the two sites. The significant climatic factors controlling the hillslope erosional processes are freeze-thaw days and precipitation. Freeze thaw days are defined as the difference between the amount of days where the minimum and maximum temperature fall under 32 degrees F. As freeze-thaw days are indicative of temperature cycling, erosion would be generally expected to increase with the number of freeze-thaw days. The effects of precipitation depends upon both the intensity and duration of an event, however hillslope erosion is generally proportional to the mean yearly precipitation.

Table 3.3.1: Climatological Data (Western Regional Climate Center)

	Healy 2 NW	Matanuska AES
Dates of Records	1976-2012	1949-2012
Elevation (feet)	149	15
Average Yearly Max Temperature	39.6	44.7
Average Yearly Min Temperature	20.3	26.5
Average Yearly Mean Temperature (F)	29.9	35.6
Annual Days of Max Temp under 32 F (days)	121	96.7
Annual Days of Min Temp under 32 F (days)	212	203
Freeze/Thaw Days (Min – Max under 32F)	91	106.3
Mean Yearly Precipitation (inches)	14.75	15.27
Mean Yearly Total Snowfall (inches)	76.7	47.7
Annual Days with at least .01 inches precipitation	100	96

Chapter 4 LIDAR DATA COLLECTION

In this chapter, we discuss how the morphology of slopes can be characterized using a combination of terrestrial LiDAR laser scanning and digital imaging.

Two field survey campaigns were conducted; one completed in 2012 and another in 2013. These campaigns collected LiDAR data at Glitter Gulch, (GG) and Long Lake (LL). At Glitter Gulch, the LiDAR data collected is between mile post (MP) 235-245 on the Parks Highway. At Long Lake on the Glenn Highway, data was collected between MP 78-89. Figure 4.1 Highlights the sections covered and shows the prioritization scheme developed based on suitability of the section for ground-based acquisition.

2012 Survey: The first survey was completed between September 4-14, 2012 by surveyors from David Evans and Associates using their terrestrial TITAN® Mobile laser scan system. Supplemental terrestrial static scans were collected using a Leica ScanStation 2 in order to capture data near the tops of various features such as cliffs and other areas difficult to capture from the roadways. This survey provided continuous data for the road segments described earlier.

2013 Survey: The second survey was completed August 1-14, 2013 by graduate students from Oregon State University (OSU). This second survey utilized a “stop and go” mobile scanning approach using a Riegl VZ-400 3D terrestrial laser scanner and GPS unit mounted to a wagon. For this survey, only the highest priority sections where cliffs were well-exposed were completed rather than the full segment.

The data were collected and processed in the Alaska State Plane North Zone 4 coordinate system using the NAD83 (2011) 2010.00 datum and the NAVD88 (Geiod12A) vertical datum in units of meters.

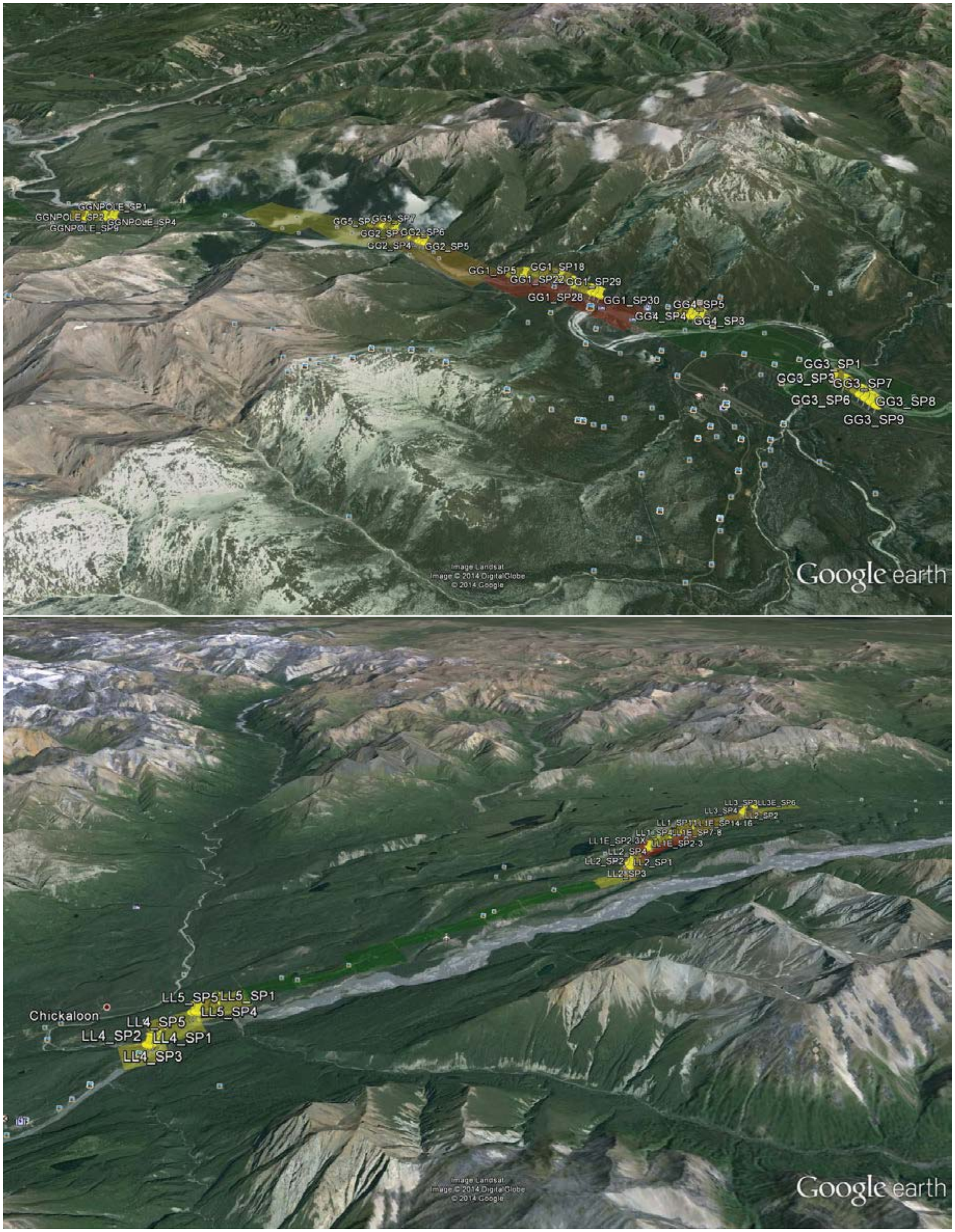

Figure 4.1 Top: Priority sections (Red->Green = Highest -> Lowest Priority) for the Glitter Gulch (Top) and Long Lake Sections.

4.1 Acquisition and Processing workflow overview

For a more complete discussion of mobile LiDAR workflows, the reader is referred to the recently published guidelines (NCHRP Report 748, Olsen et al. 2013). Herein, only the workflow and concepts relevant to this project will be discussed. Figure 4.2 presents an overview of a typical mobile LiDAR workflow and steps that are commonly completed.

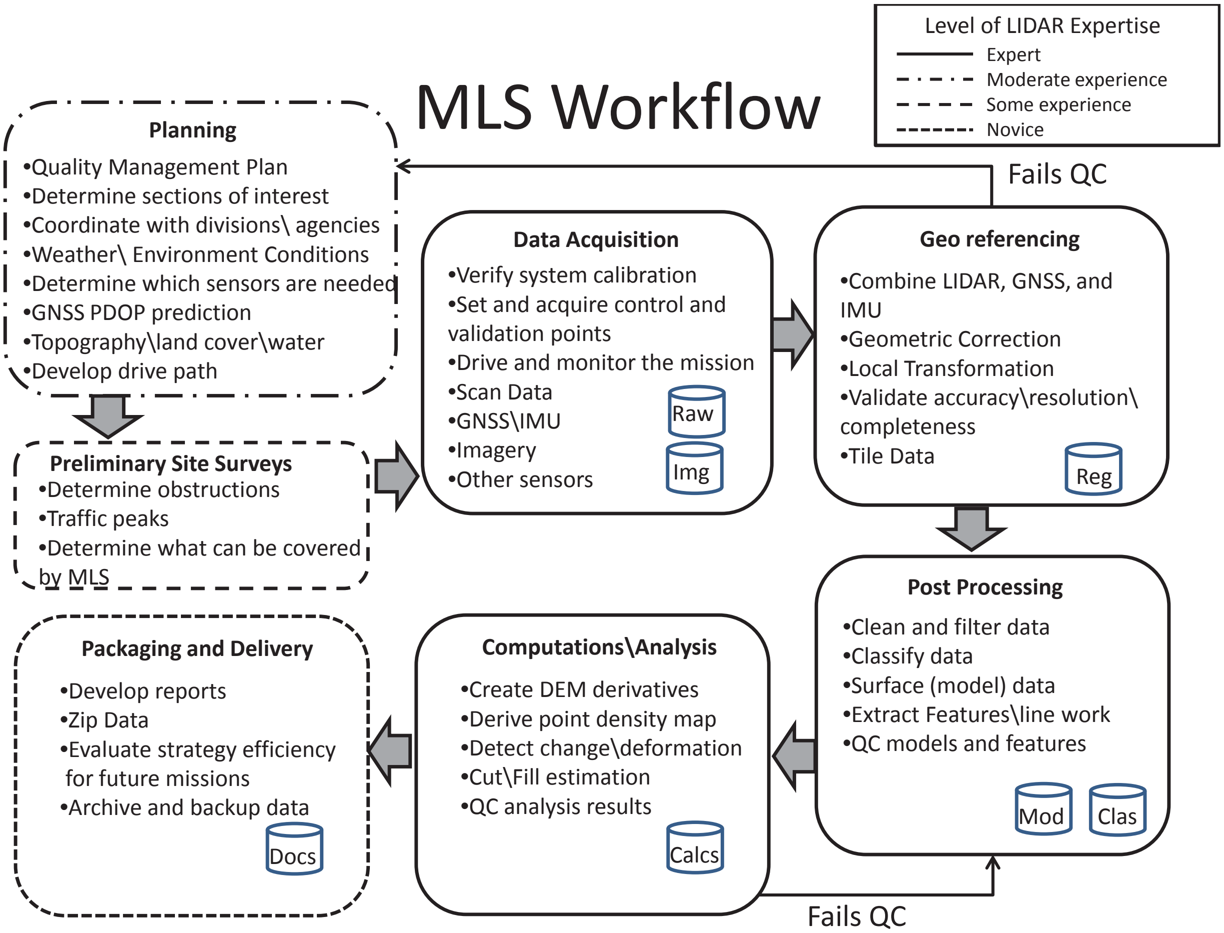

Figure 4.2 Typical mobile LiDAR workflows (modified from NCHRP Report 748, mobile LiDAR guidelines).

4.1.1 Planning

Detailed planning is the key to success for a mobile LiDAR project. Although the perception sometimes exists that one can collect data using mobile LiDAR by simply driving down the highway, high-accuracy applications require careful planning and preparation. As such, several things need to be evaluated during the planning stage. These include.

1. Safety. Although mobile LiDAR has significant safety advantages compared to traditional surveying techniques with ground field crews, safety training is still important.
2. Initial site walkthrough. A walkthrough allows the identification of locations for GPS control points, problem areas for GPS reception during scanning, and the number of passes necessary for sufficient data coverage. This walkthrough should also evaluate whether or not Mobile LiDAR will be able to capture the feature(s) of interest.
3. GPS\GNSS planning. Readily available GPS\GNSS planning software can be used to determine the optimal times for data collection. Typically, one would consider the availability of and number of satellites and their geometry (Positional Dilution of Precision, PDOP) and avoid times with a low number of satellites and high PDOP. Maintaining a PDOP less than 5 and having at least 5 satellites is recommended by Caltrans (2011) specifications. This planning is particularly important when doing work in narrow canyons, which can reduce the visibility of satellites. Most state DOTs have standards for GNSS data collection that can be helpful. These checks should be performed at multiple sites across the project area if substantial time will elapse during acquisition (e.g., more than a few hours), the site spans long distances (several miles or more), or if obstructive geometry varies significantly across the site. One should also be cognizant of atmospheric activity, such as solar flares, which can adversely affect GNSS data.
4. Determine location and spacing for validation points (points surveyed using another technique to verify the accuracy of the survey). Validation points were spaced every 300 m for this project, typically in pairs, transverse to and separated by the roadway.
5. Determine appropriate site(s) for GPS\GNSS base station. For example, based on experience, Caltrans mobile LiDAR specifications recommend that the mobile LiDAR be within 5 miles of a base station.

A critical conclusion that needs to be achieved during planning is whether mobile LiDAR will appropriately capture the desired objects as well as along which segments of the mobile LiDAR survey needs to be supplemented by additional techniques (e.g., stationary LiDAR).

The comparison of Figures 4-3 and 4-4 shows that for the proposed occupation period (from 9am to 5pm), the Long Lake site would be generally acceptable for data acquisition (PDOP <5 and # satellites > 5). However, Figure 4-4 shows that during certain time windows, particularly around 8:30am and 5:00 pm, the GPS data would be compromised since PDOP values greater than 5 would be encountered.

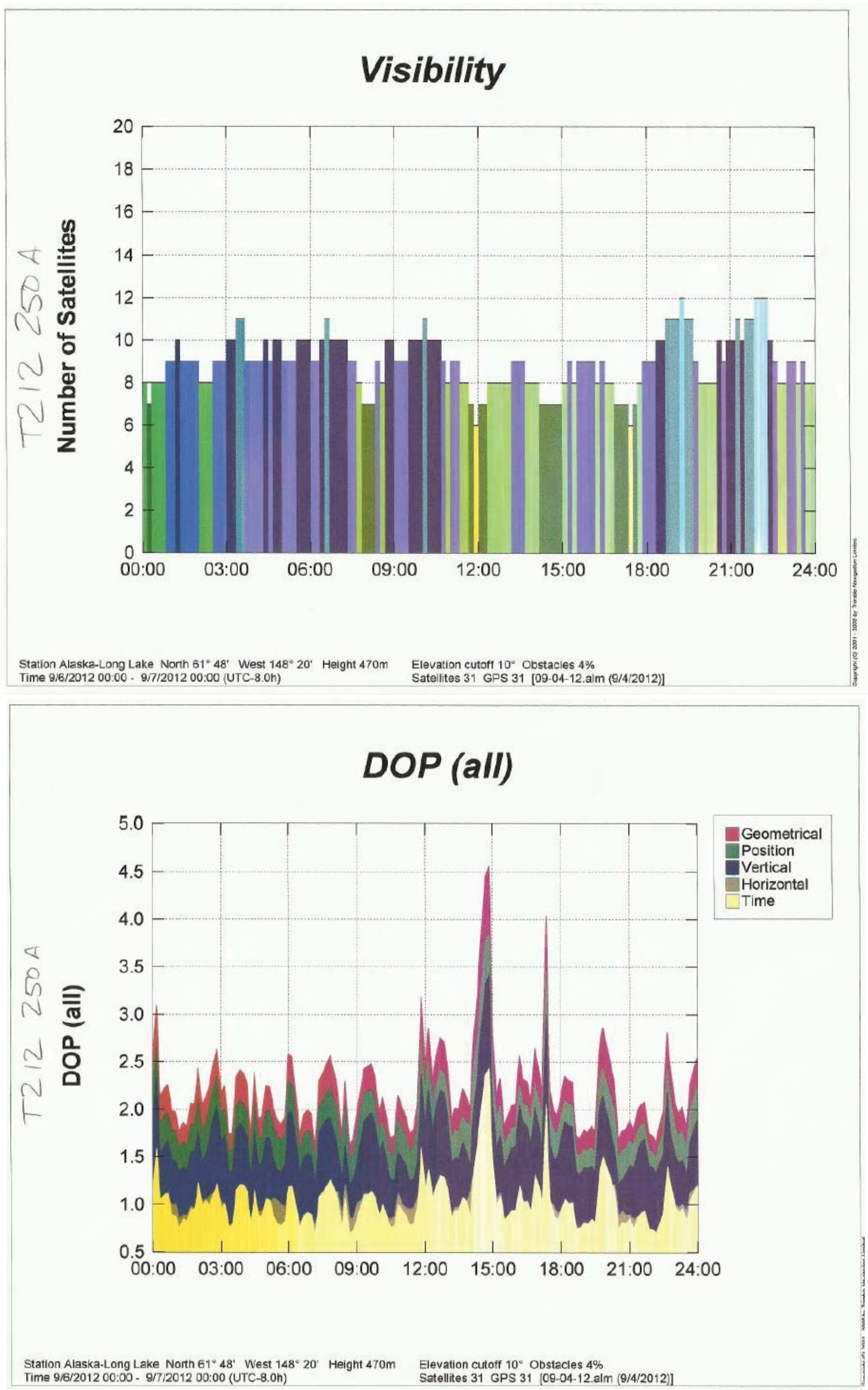

Figure 4.3 (a) GPS visibility and (b) DOP planning for a GPS base station at the Long Lake project site.

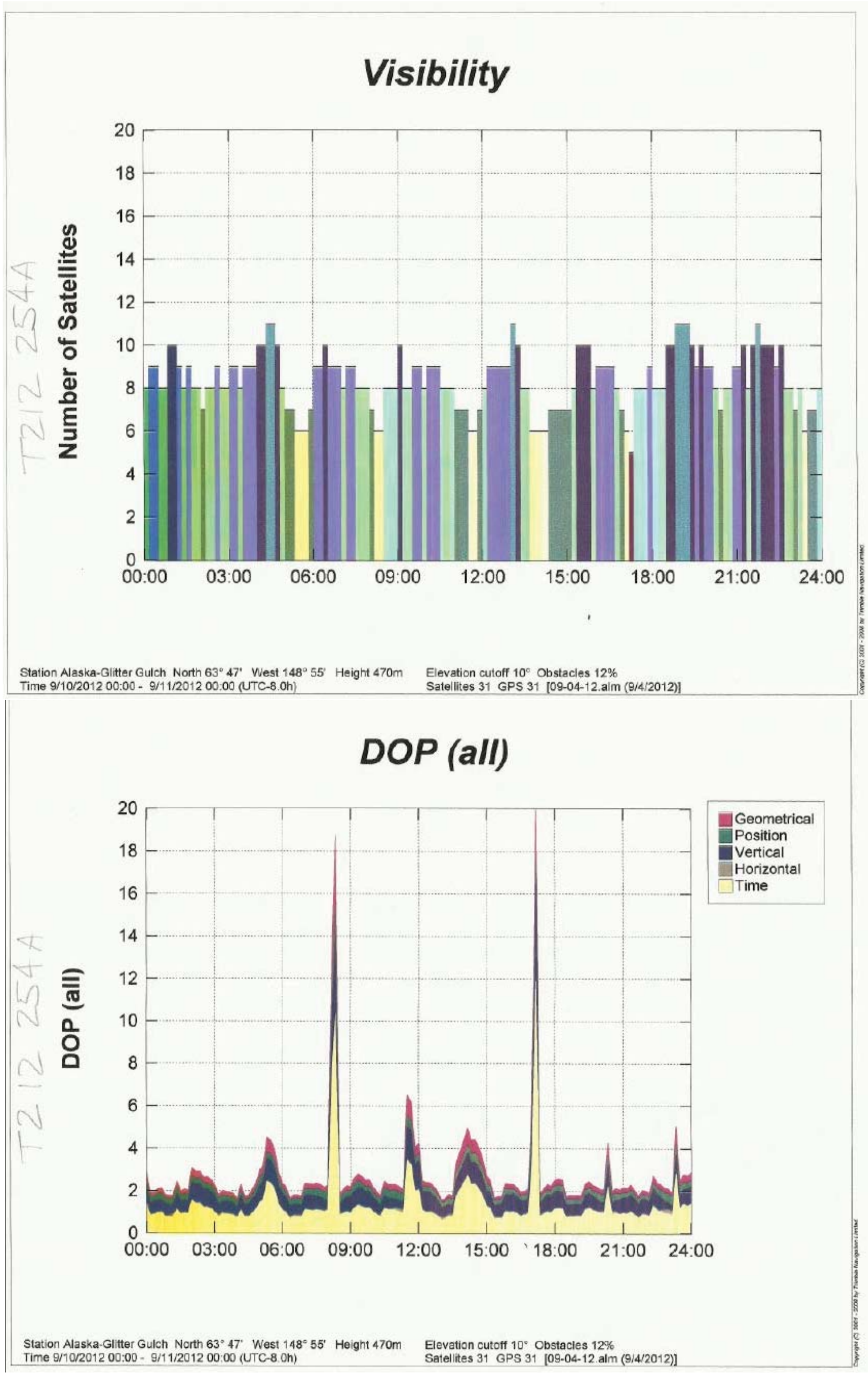

Figure 4.4 (a) GPS visibility and (b) DOP planning for a GPS base station at the Glitter Gulch project site.

4.1.1 Preliminary site surveys

A preliminary site survey was completed in June 2012 by Jon Broadwater of David Evans and Associates to prepare for and determine the feasibility of using MLS on the scan corridors and the amount of supplemental static scans required to provide a full survey. In addition, preliminary surveys were completed virtually through Google Earth® street view imagery.

4.2 Data Acquisition

Data acquisition for the two sites was completed for two surveys (September 2012 and August 2013). This section will describe the work conducted for each effort.

4.2.1 2012 Survey

The 2012 survey was completed by consultant David Evans and Associates between September 4th, 2012 and September 14th, 2012. The following work was conducted:

1. Two primary GPS control points were set at each project site and occupied for duration of approximately five hours (+/- ½ hour). The field crews used Leica 1230 GPS receivers for the primary control survey. This raw data (*.DBX file) was imported into Leica Geo Office software, then exported as a Rinex (Receiver Independent Exchange) file for submission to the National Geodetic Survey (NGS) for a rapid static Online Positioning User System (OPUS) processing. Additional control points were established using Real-Time Kinematic (RTK) GPS for referencing the stationary scans.
2. Validation points (locations used to verify the accuracy of the collected scan data) using RTK GPS were collected throughout the site, typically in pairs and on both sides of the roadway, and spaced at approximately 300 meter intervals along the highway. Additional validation points were obtained using a Leica 1202 Total Station (reflectorless) on key features (e.g. sharp edges) of the slope at the sites that were surveyed using a static scan.
3. Mobile LiDAR data were acquired through multiple passes, each verified for quality through comparison to the validation points (elevations within 5 cm, generally). Both the lanes and shoulder of the road (to the extent possible) were used to acquire the data. For example, at the Glitter Gulch site, a minimum of 6 passes were completed for the entire site and at least 10 passes were completed in the sections with steep slopes. The final OPUS positions of the base station setup locations over the control points were held fixed, and single baseline Post-processed Kinematic (PPK) measurements were made to the receiver on the vehicle generate the trajectory. These measurements are made in geodetic values for ease of calculations. The vehicle speed during acquisition was typically 25-30 mph.
4. During mobile LiDAR scanning, side and forward facing cameras obtained a video log of the corridor at 1 frame per second.
5. The mobile LiDAR was supplemented by stationary LiDAR acquired from a plumbed tripod. Reflective targets were setup in order to link scans together and

geo-reference the data so that it could be integrated with the mobile LiDAR data. Positions were established on these targets via the total station to tie them to ground control points. Four supplemental scans were completed at Long Lake and eight supplemental scans were completed at Glitter Gulch. The field of view of these scans was focused on the cliff(s).

Figure 4-5 shows an example of a merged point cloud, colored by elevation for part of Glitter Gulch.

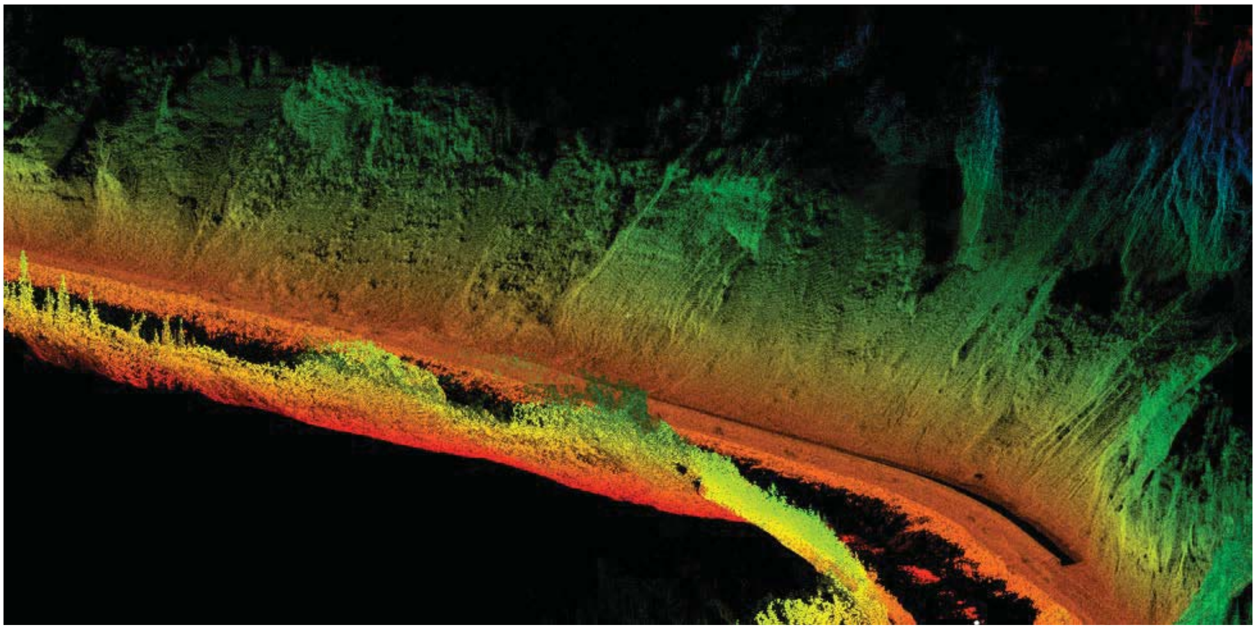

Figure 4.5 Example mobile LiDAR scan for the glitter gulch project site.

4.2.2 2013 Survey

Additional field work using a stop-and-go scanning approach was completed at both sites during August 1-14, 2013 by the Project Team. The field procedures were very similar to those presented in Olsen et al. (2009) where the scanner is mounted on a wagon rather than a tripod for efficient data collection. A Nikon D700 digital camera and a Trimble R8 GPS receiver were mounted above the scanner with calibrated transformation offsets (translations and rotations) to the scanner origin.

During data acquisition, scan positions were typically spaced at 50-80 m apart and covered a 360 degree horizontal field of view and a 100 degree vertical view (-30 degrees to +70 degrees from the horizontal plane). The resolution of the scans varied between 0.02 to 0.05 degree increments. Each position was occupied for at least 20 minutes to enable sufficient time for Rapid Static GPS data collection. Six photographs forming a 360 degree view were acquired at each scan position.

Atmospheric conditions (temperature, pressure, and relative humidity) were recorded and input into the laser scanner during data acquisition to correct distance measurements. Inclination sensors are also included in the scanner to correct for the scanner being out of plumb when conducted from the wagon platform.

For the Long Lake section, a total of 65 scans were completed, covering approximately 5.4 km (3.36 miles) of the highway. For the Glitter Gulch section, 76 scans were acquired, covering approximately 4.2 km (2.61 miles) of the highway. Table 3.1 presents quality control statistics of the field effort. Note that in both sections at least 8 satellites were observed from the GPS receiver and the PDOP remained below 5, indicating that high quality GPS data was obtained. The scan spacing was, on average, 80 m at Long Lake and 52 m at Glitter Gulch. In the Long Lake section, wider-than-ideal scan spacing was required in a few locations owing to safety concerns associated with setups in those locations of limited shoulder width.

Table 4.1 GPS and scan data quality control statistics for the Long Lake and Glitter Gulch 2013 surveys.

	Long Lake			Glitter Gulch		
	PDOP	# SATS	Scan Spacing (m)	PDOP	# SATS	Scan Spacing (m)
Average	1.8	12.2	80	1.9	12.9	52
Std Dev	0.3	2.2	33	0.6	2.7	14
Min	1.3	8.0	26	1.3	8.0	18
Max	3.3	17.0	159	4.8	18.0	80

Figures 4-6 and 4-7 show examples of point clouds collected using the static scans with RGB color information mapped to the points. Figure 4.8 shows a point cloud of the road highlighting a crack captured in the road and distinguishment of road features based on scan intensity measurements.

Figure 4.6 Close-up of the RGB colored point cloud at the Glitter Gulch project site, highlighting unstable rocks.

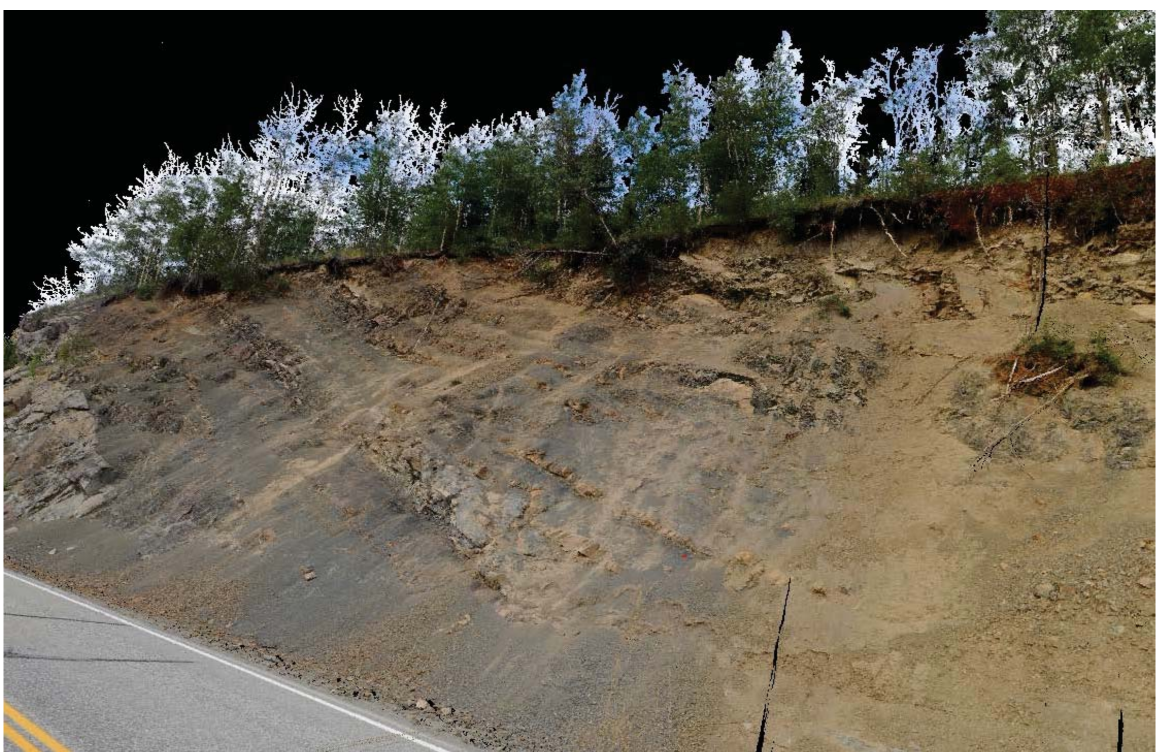

Figure 4.7 RGB colored point cloud at the Glitter Gulch project site.

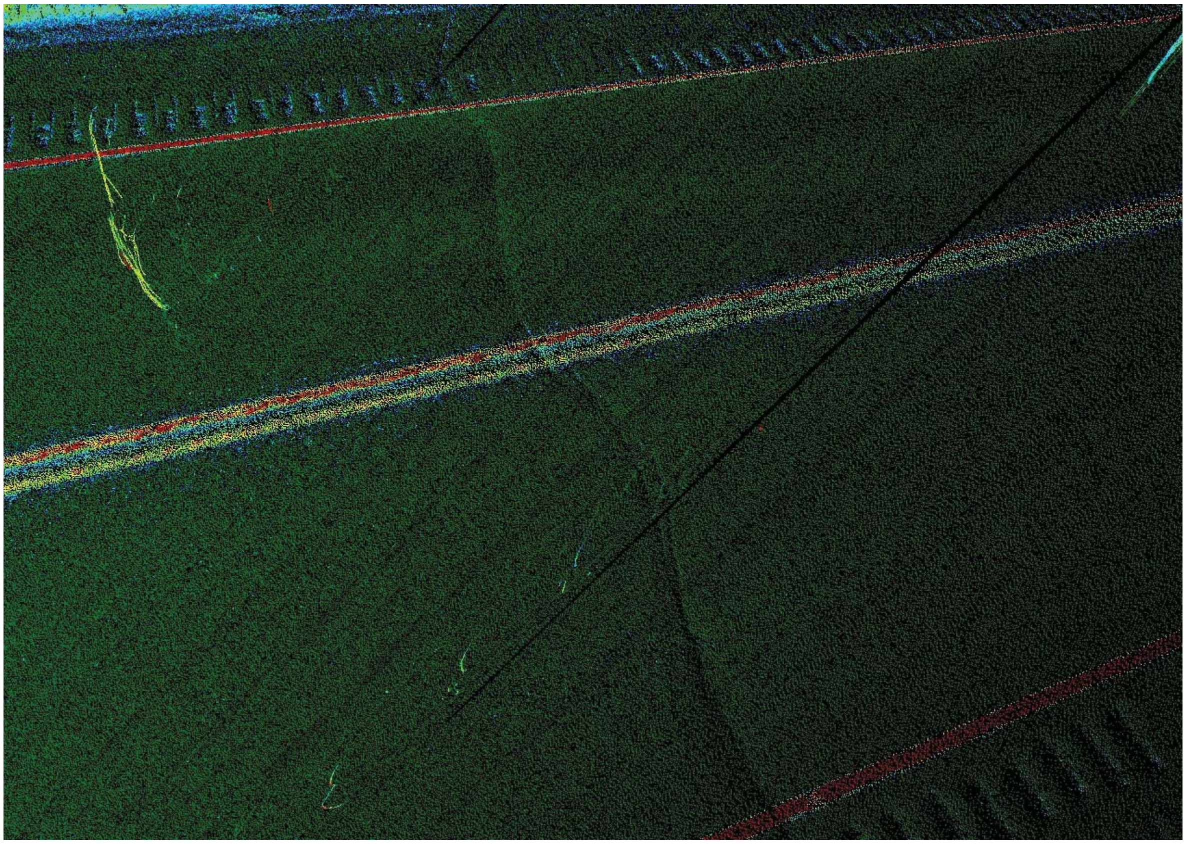

Figure 4.8 Intensity shaded point cloud highlighting a large crack observed in the road way.

4.3 Geo-referencing

Each MLS pass or each static scan produces a 3D point cloud in a local scanner coordinate system. These independent, 3D point clouds must be registered (combined) into single data set and often geo-referenced in a single coordinate system through a least squares transformation to minimize error (Brenner, 2009). To arrive at ground coordinates, point cloud data must undergo several software processing and quality control procedures to accurately position the point cloud in the desired coordinate system. Note that many elements of the workflow vary between MLS, static, and stop and go scanning. Further, individual data providers commonly have proprietary workflows and procedures to combine the data from the various sensors to produce the trajectory and geo-referenced point cloud. Oftentimes, this processing step can have the most significant influence on data accuracy, requiring substantial expertise and time spent in quality control.

4.3.1 MLS data geo-referencing

Each of the previously described components of the MLS system (see Background section) simultaneously collect and store data. For example, the GPS stores location at a point in time (typically 1 Hz), the scanner collects point locations (ranges and distances) relative to its origin (typically 1 million points per second), the Inertial Navigation System (INS) or Inertial Measurement Unit (IMU) provides high frequency (typically 1 kHz) vehicle motion data, and the color information is collected by photographic or video methods (typically 1 frame per second).

All of these data sources are precisely time-stamped for integration (Reiger 2010). The INS is typically used as the point of reference for the calibration and data processing.

Because there are multiple components of a Mobile LIDAR system (Figure 4-9), each operating in its own coordinate system, the offsets and angles between each component need to be calibrated. This is typically done by the manufacturer and is valid as long as the components are not dismantled. However, given wear and tear on the system from road vibrations and usage, a calibration is typically done yearly and before critical projects that require the highest level of accuracy. Prior to each data acquisition in the field (and often following), a calibration check is performed.

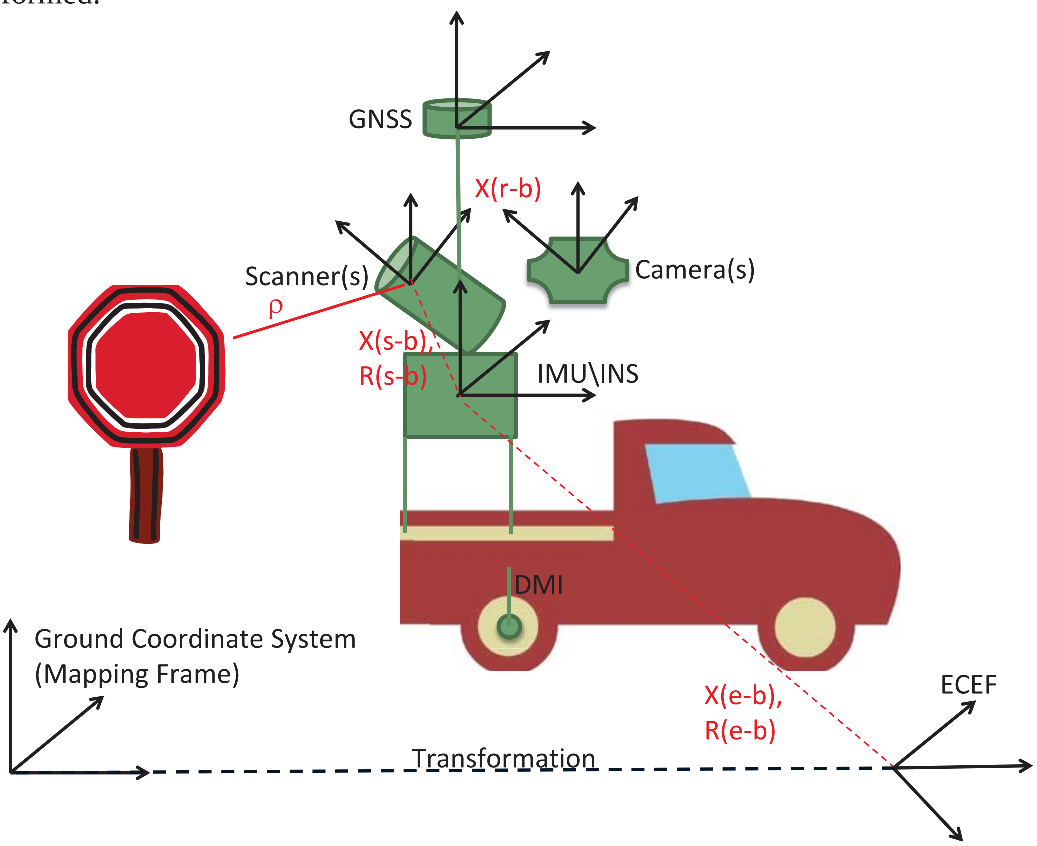

Figure 4.9 Coordinate transformations for MLS (from NCHRP report #748).

There are a variety of workflows to geo-reference MLS data. The procedure employed by the consultant follows:

1. The GPS data collected on the control points used as a base station were downloaded and submitted to the National Geodetic Survey (NGS) website Online User Positioning Service (OPUS) for processing relative to nearby Continually Operating Reference stations (CORs).
2. The GPS data from the GPS unit on the MLS system and the GPS data from the base station were downloaded as RINEX (a receiver independent exchange format) files.
3. The GPS data from the MLS system was then processed using post processed kinematic (PPK) GPS methods using the base station data. PPK compares the GPS data collected at the base station during the MLS acquisition to the

coordinates obtained in Step 1 for the base station, providing correctors for ionospheric disturbance. These corrections are then applied for each time step for the GPS data collected on the MLS.

4. The INS and distance meter data were downloaded.
5. For each pass, the GPS data, IMU, and distance meter data were processed and combined to obtain the vehicle trajectory using a Kalman Filter. This step was done using custom software provided by the TITAN® manufacturer. Essentially, a Kalman filter uses the higher frequency IMU data to fill in the gaps between the GPS data, particularly in areas of GPS data outages. The GPS data are more accurate across larger distances where drift occurs in INS systems. However, over small time increments (<60seconds), the INS system can provide improved relative accuracy. The Kalman filter exploits this. Both a forward and backward (direction of trajectory) solution are combined to minimize error from drifting.
6. Once the trajectories were established and the orientation of the vehicle was determined at each point in time, the angles and distances measured by the scanner were then used to calculate ground coordinates on an object.
7. Once each pass has been processed, a strip adjustment can be performed, if necessary, to minimize biases between the multiple data passes.

Other methods (e.g., Barber et al., 2008) can be used to improve accuracy such as registration to targets (typically reflectors or patterns), high-resolution terrestrial laser scan (TLS) data, or ground control points surveyed through more traditional methods such as a total station. These adjustments are typically called geometric corrections. The consultants' system can compute ground coordinates without the use of targets. Establishing coordinates for additional targets can be time consuming to place and measure, thereby decreasing the efficiency of the field effort.

For interested readers, the mathematical theory for calculating ground coordinates on objects can be found in various publications on kinematic scanning (e.g., Baltsavias, 1999; Glennie, 2007). A brief summary is also found in the NCHRP Report #748 providing mobile LIDAR guidelines.

4.3.2 Static scans in the 2012 and 2013 surveys

Geo-referencing is a critical step to relate data from different time intervals. Since each scan is normally recorded in its own scanner coordinate system, one scan is not relatable to another unless it is transformed into a common coordinate system. This is generally accomplished through a least squares, rigid-body coordinate transformation, determining both rotations and translations along orthogonal axes, which results in the minimization of the sum of the square errors between point pairs (either from pre-marked targets or matching points in the point cloud).

In the 2012 survey, a target resection process was employed by the consultant to geo-reference the scan data. This process includes:

1. Setting up targets that are easily identifiable (e.g., reflective or a distinguishable pattern) and precisely measured in size;
2. Acquiring high resolution scans of the target and using algorithms to determine the center of the target;

3. Using a total station to reference the target centers to GPS control points on the ground (a prism on a pole is used over the GPS control points and reflectorless mode is used on the target centers); and,
4. Performing a least-squares rigid body transformation of the target points found in the scans to the control coordinates established.

For the 2013 survey, both the baseline and in-situ scans were geo-referenced using the methodology presented in Olsen et al. (2009, 2011) using the program PointReg. The methodology was developed for efficient surveying in dynamic environments (e.g., coastal areas, active landslides) where survey control can be difficult to establish and maintain. Although other geo-referencing procedures can be implemented, such as the approach implemented in the 2012 survey, the PointReg approach can minimize field time since targets are not required (Williams et al. 2012).

During the field data collection, the operator obtains most of the geo-referencing transformation parameters needed for scan alignment. Translation vectors (X, Y, Z) were obtained for the scanner origin using RTK GPS, corrected for offsets between the scanner origin and GPS antenna reference point (accounting for a slightly out of level setup, typically <1 degree). The rotations about the X (roll) and Y (pitch) axes are determined using internal inclination sensors in the scanner. Silvia and Olsen (2012) highlight the importance of these sensors and their ability to provide quality data for scan geo-referencing. The azimuthal values for scan positions are initially estimated using a digital compass and then converted into a rotation about the Z-axis (yaw). This angle is then improved using the least squares solution presented in Olsen et al. (2011), which calculates the optimal rotation of a scan about the Z-axis (centered at the scan origin) to best fit with neighboring scans.

However, a few updates were made during this project to the methodology of Olsen et al. (2011) to improve processing. Most notably, the algorithm now enables an adjustment of translation in the Z direction for each scan based on biases observed between adjacent scans. To avoid systematic error propagation, the scans are not able to shift far from the GPS coordinates measured at the scan origin.

4.4 Data post-processing

For Phase I, the remainder of the data processing was only completed for the high and very high priority sections collected during the 2012 surveys. Additional processing will be completed during Phase II for the 2013 surveys, which was beyond the scope of the first phase.

4.4.1 Filtering

Following registration, point cloud data is typically filtered to eliminate unwanted features, including what are termed “artificial low points”, where the laser reflects off of water onto another surface and then back to the scanner, objects passing in the scanner view (e.g., passing cars), unwanted vegetation, or, more generally, anything that is not needed by the end user.

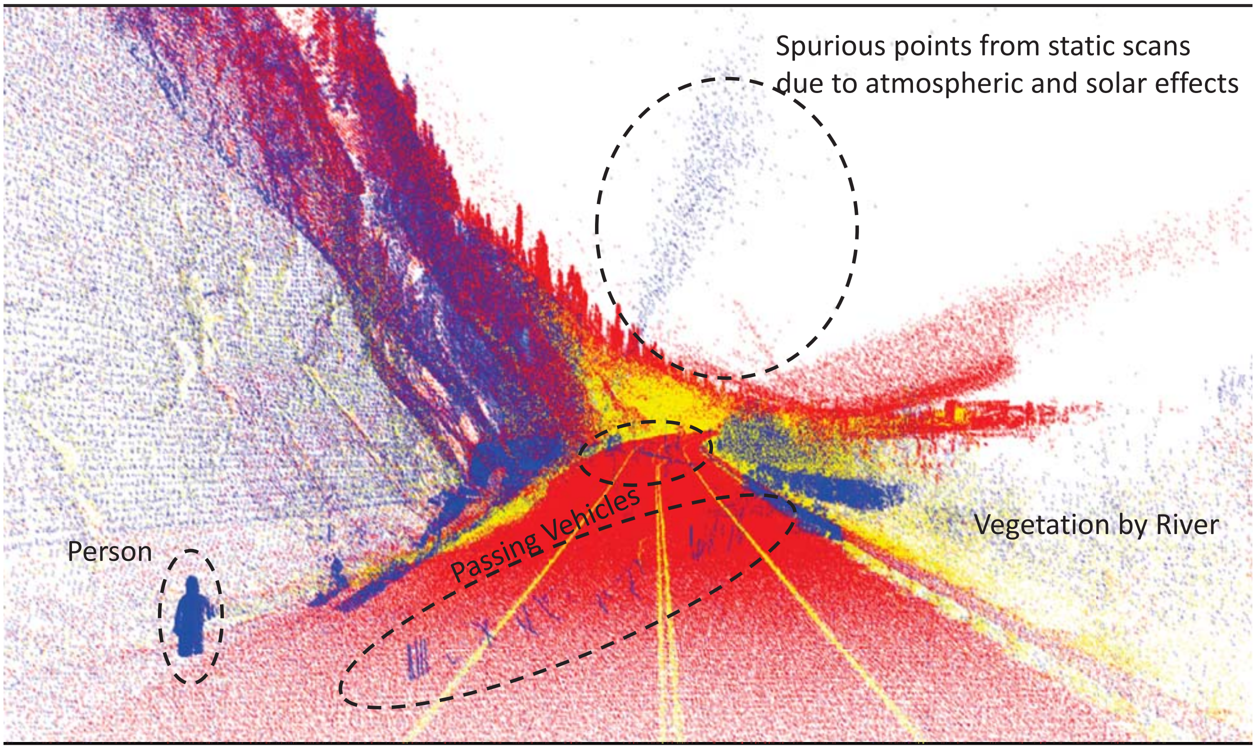

Figure 4.10 Examples of noise removed from the scan data.

Filtering processes vary substantially in the degree of user interaction required and the type and quantity of noise present (e.g., Figure 4-10). For the datasets collected in this study, passing cars, noise from moisture in the air, and low points resulting from reflection off of the water surface were all removed manually using Leica Cyclone software to create polygon windows around unwanted objects. Rather than deleting the points, they were placed on a layer entitled "noise."

Stray points from passing vehicles were removed as well as erroneous points due to solar or wet surface reflections. However, features such as trees and vegetation were not removed at this stage, but are later removed through a more-efficient filtering process. To facilitate the creation of terrain models, two point cloud files were exported for each section after this manual cleaning stage: one that included all of the remaining points and one that only included points on the cliff face.

Leica Cyclone software was used for point cloud editing using the following steps:

1. Created a new modelspace for each section, containing only the data points in that section.
2. Points that were easy to remove in 3D were deleted while showing the entire scene. Note that because data editing is performed on a 2D monitor with a 3D dataset, one has to be very careful to ensure that only the points of interest are selected for removal. Oftentimes, there will be points behind those points in the 2D view that are not visible, but will be selected through the 2D interface. Hence, most software enables one to add and remove points from a selection when changing views.

3. Cut-planes (i.e., cross-sections) with widths of approximately 50 m were used to facilitate editing noise by focusing on smaller sections, reducing the problem discussed in Step 2.
4. Points on the cliff surface were extracted to another layer called “cliff” so that they could easily be extracted for 3D triangulation creation.

4.4.2 Ground filtering and modeling

As mentioned previously, vegetation points were left in the dataset due to difficulty associated with removing them manually. A DEM was created by statistically filtering points using a program “Bin ‘N Grid.” (Olsen 2011). This program was adapted and enhanced via this research project in order to improve processing speed, quality control verification, and to provide new exporting capability. The basic operating procedure of Bin N Grid is as follows

1. Divide the point cloud into small cells with the desired cell size, Δ (e.g., 0.2 m x 0.2 m), which is constant in X and Y. The number of rows and columns are determined by:\

$$N_x = \frac{ceil[ceil(X_{max}) - floor(X_{min})]}{\Delta} \quad (2.1)$$

$$N_y = \frac{ceil[ceil(Y_{max}) - floor(Y_{min})]}{\Delta} \quad (2.2)$$

Where: NX and NY = the number of columns and rows in the X and Y directions, respectively, and ceil is a function that rounds a value upwards to the nearest whole number, floor is a function that rounds the value down to the nearest whole number, Xmin and Ymin are the minimum X and Y values in the dataset, and Xmax and Ymax are the maximum X and Y values in the dataset. A point is then assigned to a grid cell by the following equations:

$$I_x = \frac{floor(X_i - X_{11})}{\Delta} \quad (2.3)$$

$$I_y = \frac{floor(Y_i - Y_{11})}{\Delta} \quad (2.4)$$

$$I_{xy} = I_x + I_y * N_x \quad (2.5)$$

where: I_X and I_Y = the cell index in the X and Y dimensions, X_i and Y_i = the X and Y coordinates of the i^{th} point, X_{ll} =the coordinates of the lower left corner of the dataset (rounded down to a whole number for simplicity), and I_{XY} = the cell’s index in the grid, represented as a 1D array. For searching and computation efficiency, the points are then sorted by their index so that points are grouped by cells.

2. Statistically evaluate the elevation values within a grid cell to determine an appropriate value for each grid cell. For this project, the Z value used for the cell was the median if the standard deviation of the elevation values was relatively small (e.g. 0.05 m). If the standard deviation of elevations values were larger, the higher of the minimum value and the mean minus two standard deviations was used. While oftentimes the minimum value is used, it can be prone to error, particularly in wet areas.

3. This gridding process can also automatically eliminate off-surface points generated from passing vehicles (such as using minimum values in grid cells) or reduce systematic instrument noise (using average or median values in grid cells). Multiple grids were created using a range of cell sizes to understand the influence of sampling interval on the results.
4. At the time of processing, an output grid showing the number of points per grid cell is also generated. This grid provides the resolution\point density of the dataset and is useful to identify areas with high confidence of successful ground filtering (high point density) versus areas of low confidence (low point density).
5. The program creates a grid in ESRI Band Interleaved by Line (*.bil) format, outputs statistics for the grid, and a projection file.

Various cell sizes (e.g., 0.1, 0.2 0.5 and 1.0 m) were used to create the grids to explore the optimal cell size. However, a 0.2 m grid offered the best compromise between preserving detail, maintaining accuracy and minimizing holes (i.e., data gaps) within the grid. Note that a constant cell size works well for most airborne laser scanning where point sampling is relatively uniform. However, in MLS and static scanning, there is a higher density of points close to the scanner that degrades with distance and obliquity to the surface. Hence the data were cropped to focus only on areas of sufficient detail to produce reasonable results.

4.5 Quality Control Procedures

There are several measures of scan geo-referencing quality that are independent of the method used to geo-reference the data. The amount of time spent on these quality control measures should be representative of the project QA/QC requirements and quantity of data generated. In the case of slope stability studies, one will want to spend significant time to make sure that scan data are consistent so that detected change between surveys are reliable. Below are some examples:

1. An external dataset (e.g. topographic points acquired with a total station or RTK GPS, depending on accuracy requirements) are useful for validation of the geo-referencing quality (Table 4.10, Figure 4.11). However, this requires additional field time, equipment, and personnel. Hence, one needs to strategically plan the location of these validation sample points.
2. Root-Mean Square (RMS) fit values are provided following geo-referencing or strip adjustments in most commercial software to provide a mathematical evaluation of accuracy. These values, however, can be influenced by obstructions (e.g. vegetation, people, etc.) in the scan scene.
3. Visual checks and verifications should be performed. Although large misalignments are generally easy to spot when visually inspecting the data, subtle misalignments require extra attention.
    i. One check is to color each scan or MLS pass a different color and examine areas of overlap to ensure a good match (Figure 4.12). When one color is predominant, it indicates a problem in the geo-referencing of one of the scans or passes. Rather, the colors should blend together in areas of overlap. Note that there may still be some sections where one color tends

to dominate due to increased point density or because that location was only visible from one scan or MLS pass.

ii. Visual examination of cross sections can help evaluate the effectiveness of geo-referencing. Scans that are misaligned will appear as multiple, disjointed profiles, rather than a single, cohesive profile.

4. Comparison of datasets between epochs on features that are not expected to move aids analysis. One can evaluate the consistency between multiple surveys to locate geo-referencing errors. However, caution must be used since some objects assumed to be stable may, in fact, be moving due to landslides or creep. When a long time series of data are available, these differences are easier to resolve.

For the 2013 survey, RMS differences between overlapping sections of adjacent scans were used to evaluate data quality. These differences were typically in the range of 3-4 cm (3D) for both project sites. However, in some cases, RMS differences were as high as 7-8 cm in areas with poor GPS data quality.

Table 4.2 Summary statistics of elevation data validation for the Long Lake and Glitter Gulch sites from the 2012 Mobile LIDAR survey.

Δz (m)	Long Lake	Glitter Gulch
Average	-0.003	-0.008
Minimum	-0.179	-0.087
Maximum	0.093	0.067
Average (absolute)	0.020	0.025
RMS	0.035	0.031
Std. Dev	0.035	0.030
95% confidence	**0.069**	**0.061**
# validation points	169	124

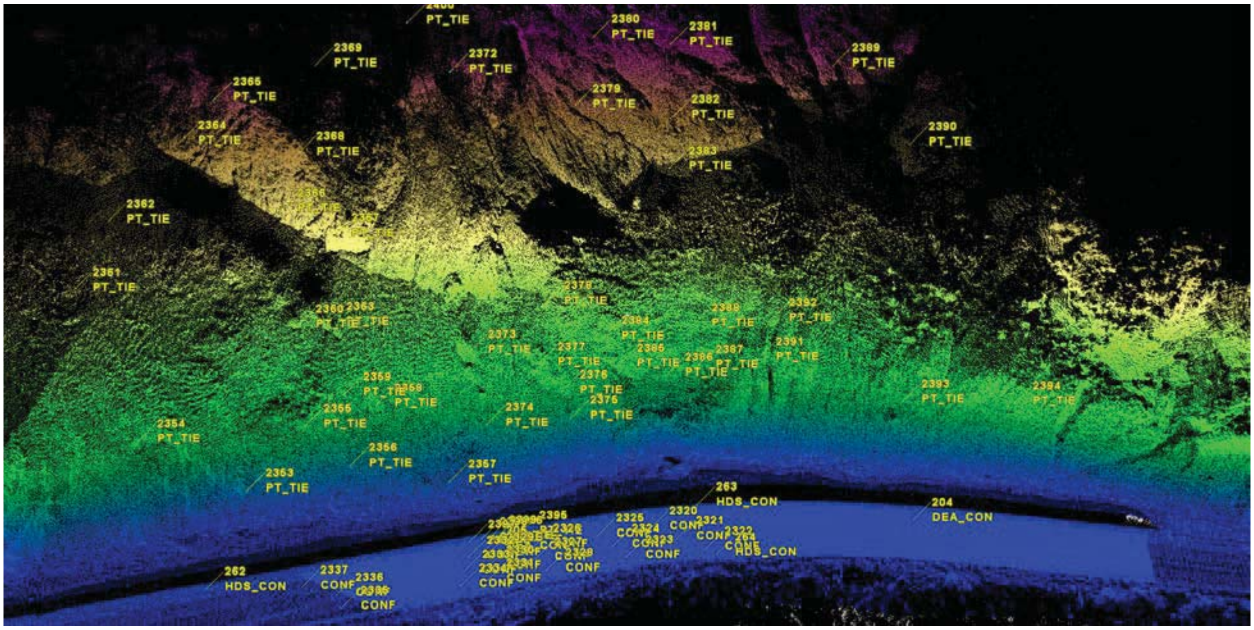

Figure 4.11 Example of validation points collected with a total station.

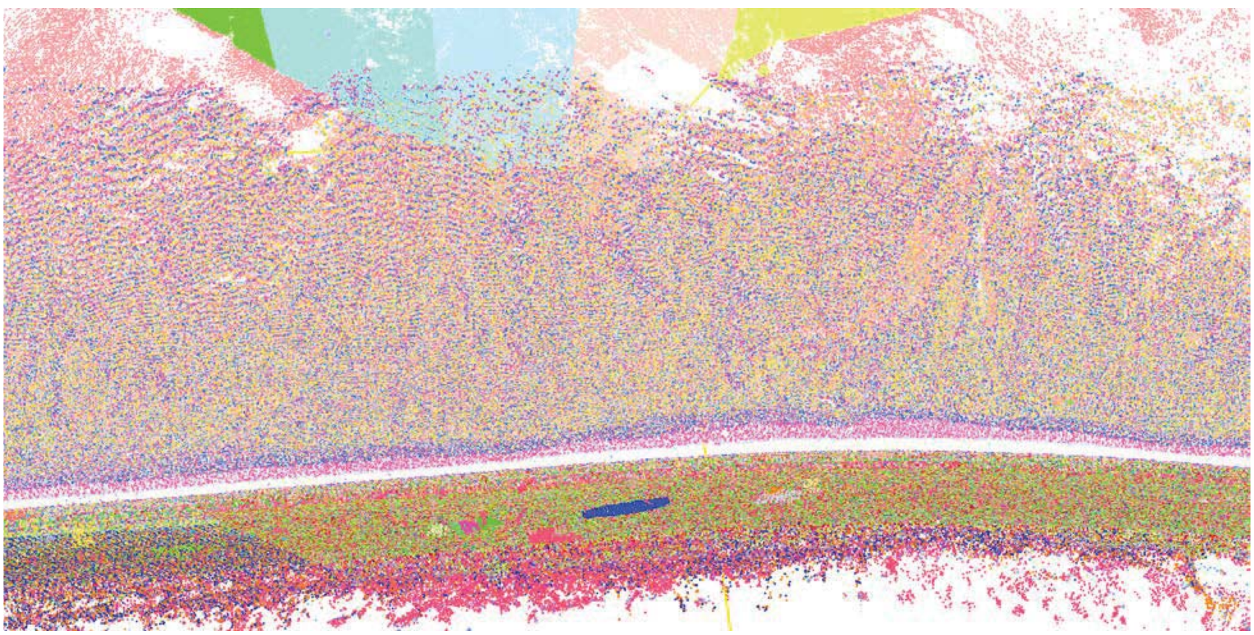
Figure 4.12 Example of blending between multiple LIDAR passes and static scans.

4.5.1 Data prioritization

In order to provide timely results in the project, a prioritization scheme was implemented so that the highest priority sections could be completed first (Figure 4.1). The highest priority areas were steep cliff sections, which are ideal candidates for MLS evaluations due to the look angle of the sensor directly on the cliff face. This sections were also generally highly unstable.

Chapter 5 Results

The LiDAR data collection resulted in several data sets being created and manipulated to derive information useful for slope stability analysis.

5.1 Digital Elevation Model (DEM) processing

Following creation of an initial DEM, holes were filled using a custom algorithm, similar to focal statistics in GIS. The algorithm searches neighboring cells (in a user specified window, typically 5x5 cells for a 0.2 m cell size) and returns the average of all cells in that neighborhood as the elevation for the grid cell with no data.

The 0.2 m grid generally contained small holes (<5 pixels in size) in most of the area of interest on the slope. Hence, this interpolation technique was successful in filling most of those holes without extrapolating values across a large range. However, when large holes are present (>10 pixels in size), one should consider using a larger pixel size or leaving a data gap, rather than filling.

Visual checks were then performed on the DEM to determine if the point cloud needs additional editing and the process was repeated until the majority of the artifacts were removed.

5.2 Derivative Products

Multiple derivative products can be generated from the DEM. Figure 5-2 summarizes products created for this project including, slope, aspect, hillside, plan curvature, profile curvature, and surface roughness. Each of these derivative products are useful for analyzing the terrain an areas that are more susceptible to failure due to inconsistencies in the ground surface.

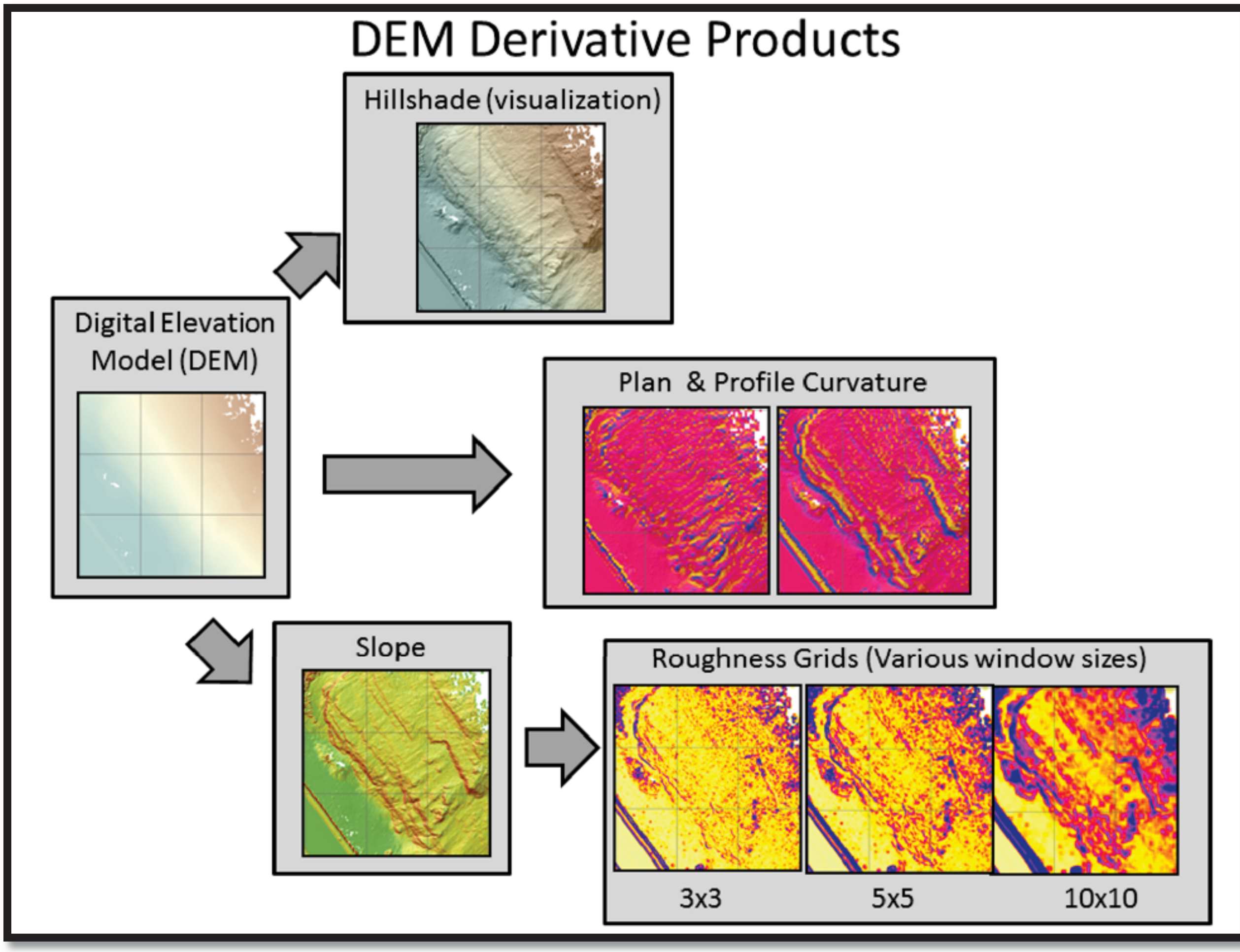

Figure 5.1 Schematic illustrating derivative products generated from the DEM.

1. Slope - Slope can be defined as the rate of change in elevation values, usually expressed in degrees ranging from 0 to 90 degrees. There are a variety of GIS-based techniques to calculate slopes using a grid-based DEM. The approach employed by ArcGIS uses the following process to determine slopes considering adjacent cells in all directions (Figure 5.2):

a	**b**	**c**
d	**e**	**f**
g	**h**	**i**

Figure 5.2 Process used to calculate slope based on neighboring pixels.

Using the elevation values from the adjacent grid cells (Figure X-2), the slope is calculated in cell "e" as follows:

$$\frac{dz}{dx} = \frac{(a + 2d + g) - (c + 2f + i)}{8 \times x\dim}$$

$$\frac{dz}{dy} = \frac{(g + 2h + i) - (a + 2b + c)}{8 \times y\dim} \tag{5-1}$$

$$\frac{rise}{run} = \sqrt{\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2} \qquad \deg = \tan^{-1}\left(\frac{rise}{run}\right)$$

Custom code was created to generate slope grids in C++ for faster processing.

2. Aspect - Aspect indicates the azimuthal direction of the maximum slope for a grid cell, in degrees. It is calculated based on the dz/dx and dz/dy components in the equation above. (Aspect = $\tan^{-1}$((dz/dy)/(dz/dy), converted to an azimuth value between 0 and 360^o). The aspect grids were created using ArcGIS functions.

3. Curvature – Curvature is the rate of change of slope. Specifically, plan curvature evaluates how slope varies within a plan view. Profile curvature evaluates the change in slope on a 2D, elevation view profile. Both of these grids were created using ArcGIS functions.

4. Roughness – An automated algorithm was developed to determine the roughness. The definition of roughness for a pixel used in this study was the standard deviation of slope within a window (See discussion of roughness metrics in Chapter 2). Window sizes of 3x3, 5x5, and 10x10 cells were evaluated.

5.3 Triangulated surface mesh creation

The previous GIS-based products are not actual 3D surfaces, but are 2.5D, plan-view products because they do not allow for multiple Z values per X, Y location (Figure 5.3). Such techniques perform reasonably well for flat surfaces, with minor variability. However in the case of steep surfaces such as the slopes in Glitter Gulch and Long Lake, 3D surfaces produce better interpretative models because they can be generated from multiple views orthogonal to various sections of the cliff. However, there are limited software packages that can adequately analyze 3D models. In addition, many software packages perform volume calculations in plan view and cannot be adapted to the more complex 3D models.

For select sections of slopes with exposures of cliff faces, 3D, triangulated surface meshes were created using the method outlined in Olsen et al. (2013). This method bins points along the surface of the slope, determines the centroid of the points within the bin (removing outliers), and then triangulates centroid points in neighboring bins to produce a 3D surface model (Figure 5.4). Figure 5.5 shows an example of these models with texture mapped color information.

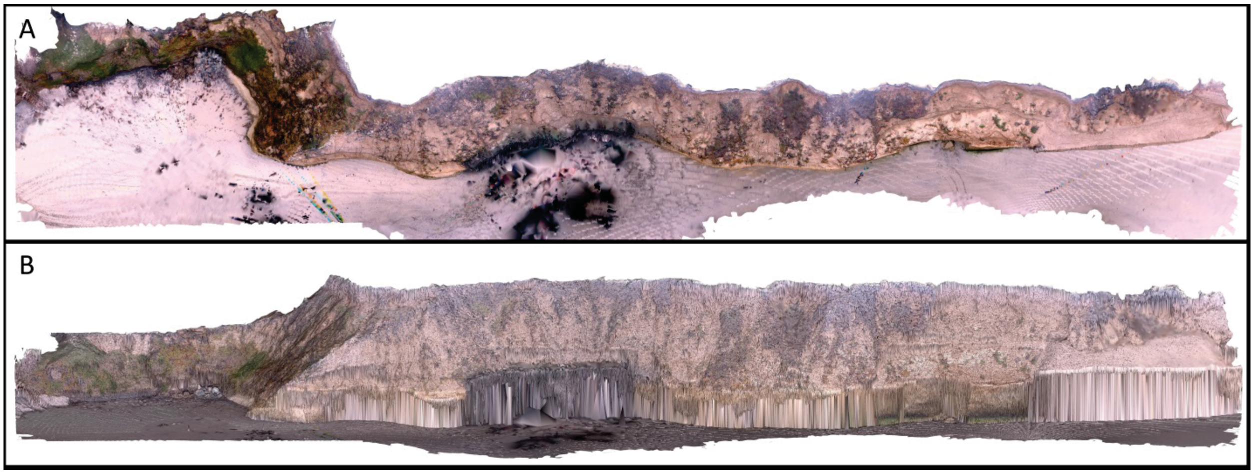

Figure 5.3 2.5D Delaunay Triangulation (A) from plan view and (B) direct view of cliffs. Note the poor modeling on near vertical features and overhangs that are not observable in plan view (A) but are in the direct view (B).

From these 3D surface meshes, derivative products such as 3D curvature and roughness can also be created. The project team explored options for these processes in *CloudCompare*, an open source program developed for analyzing change in point clouds. The results of the 3D analysis showed similar results to the 2.5D analysis; however, roughness from overhangs and on steep sections of the cliff face were better preserved.

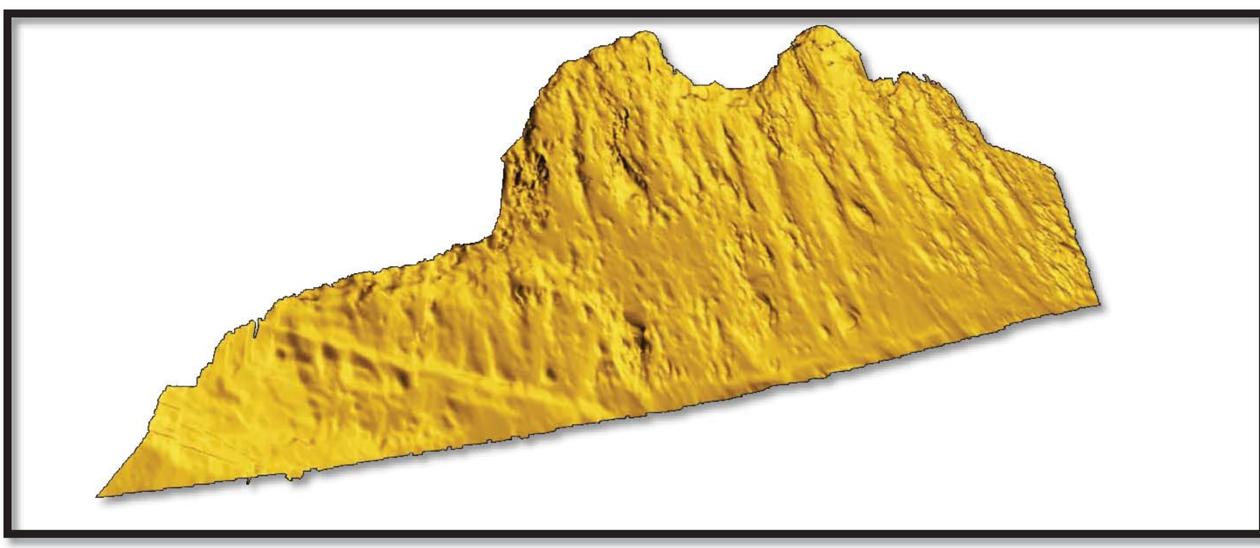

Figure 5.4 Example of a triangulated surface mesh for a section at the Long Lake site.

Figure 5.5 Example of a texture mapped surface mesh for Glitter Gulch.

5.4 Preliminary Change Detection

Although a detailed change detection investigation between surveys will be completed in Phase II of the project, during Phase I, a preliminary change analysis was done for a small section of the glitter gulch section (Figure 5.6 and 5.7). These analyses were completed in Maptek I-Site Studio, v4.2 software. In these images below, blue represents erosion and red represents accretion of material. Overall, detectable change was observed beyond the positioning errors of each dataset.

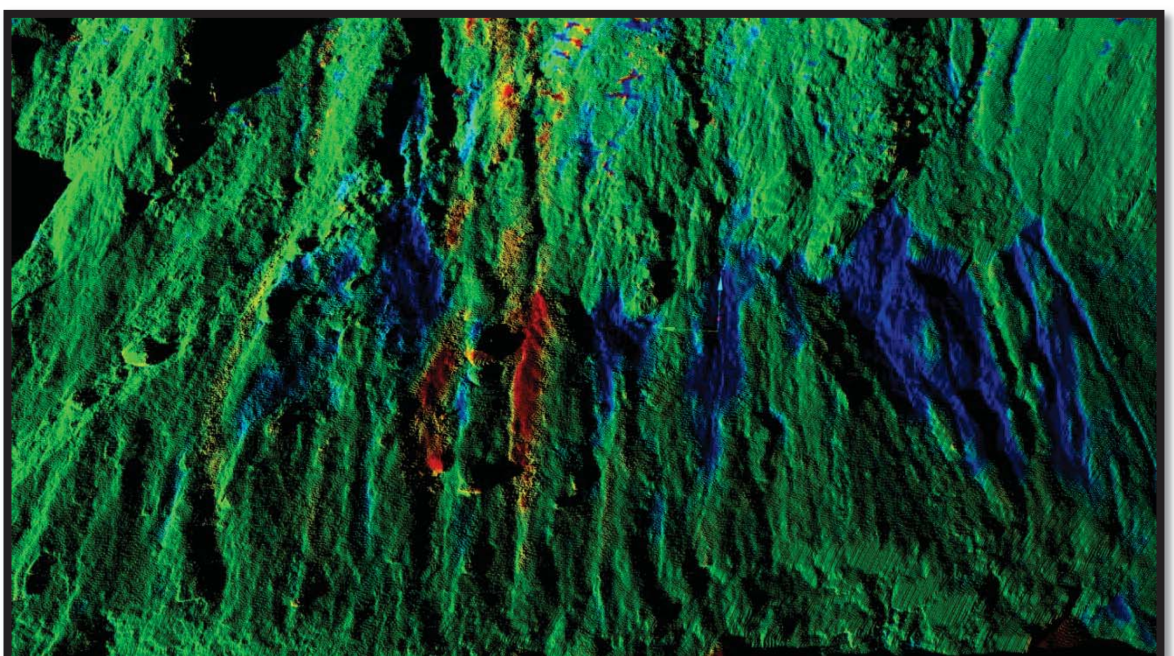

Figure 5.6 Close-up of eroded material (blue <-0.25m) on an upper section of the slope at the glitter gulch project site.

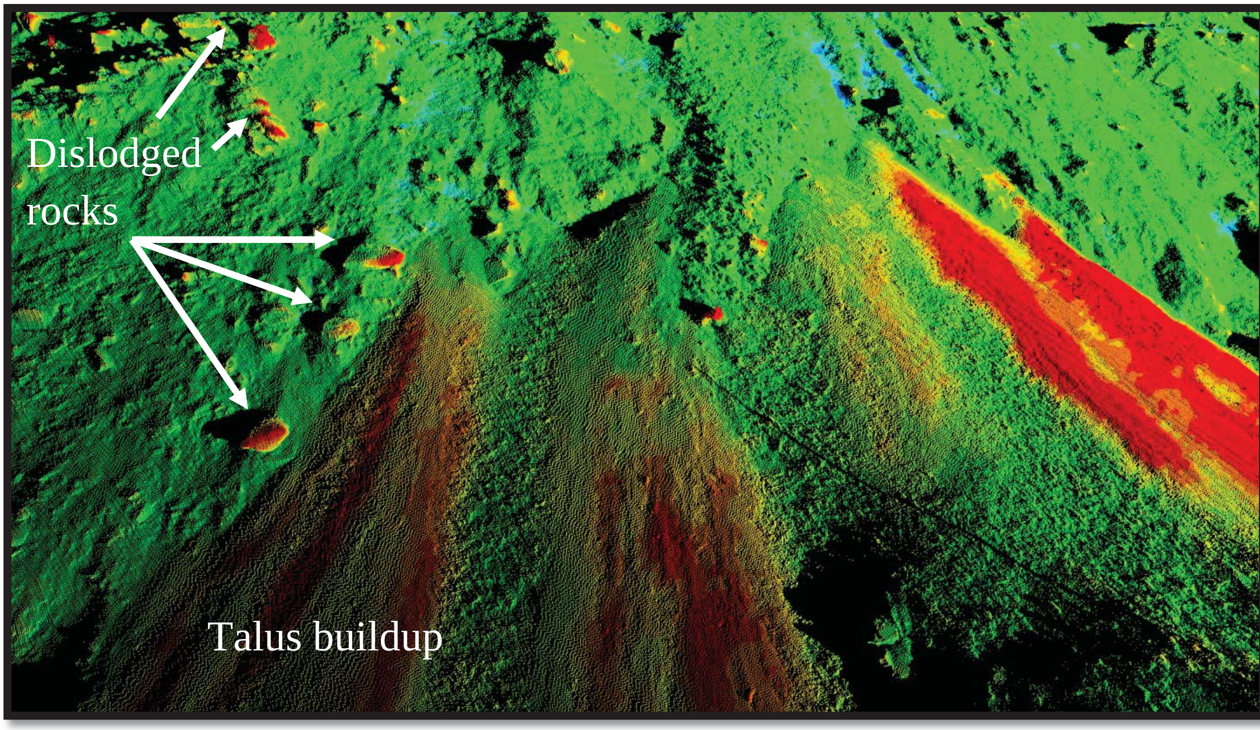

Figure 5.7 Close-up of accreted material (red > 0.25m) and eroded material (blue <-0.25m) at the glitter gulch project site.

5.5 Slope Change using RDA and RHRS systems

To understand better what is driving the slope changes, an investigation into classification systems and their required factors was undertaken using the Rockslope Deterioration Assessment (RDA) and the Rockfall Hazard Rating System (RHRS). This helped to establish a baseline behavior of the slopes and to characterize the important factors leading to failure.

Not all of the factors that are measured in the RDA and RHRS system are readily measured with LiDAR. The two systems are flexible in that they allow factors to be removed or added. The factors used in this characterization of slopes needed to be able to be measured by remotely, including LiDAR, photos and use of Google Earth Street View, and online databases.

Some of the factors were easy to measure or derive from the LiDAR and Digital Elevation Model (DEM) that was derived from the LiDAR data. Other factors were assigned based on a relative scale because exact measurements were not possible to make from photographs for example fracture aperture. Other factors were assumed or disregarded in the final iteration of the analysis because there was no significant difference between sites for example excavation methods. One factor— the compressive strength of the rock— was not possible to measure remotely. For this factor, assumptions were made using the type of rock until a second field study was be conducted in August 2013 and measurements were taken with a Schmidt Hammer (Goudie 2006). A complete history of rock falls does not exist to suport assignment of a rockfall history factor. Therefore, assumptions were made when assigning this parameter by looking at talus piles and debris in ditches. Table 5.1 summarizes the factors and how they were measured.

Table 5.1 Factors and how they were measured

Factor	Data Summary
Altitude	Geographic Information Systems (GIS) using Digital Elevation Models (DEM) maps
Aspect	GIS using DEM maps
Rock Weathering	From photos, Google Earth, LiDAR
Stabilization and Protective measures	LiDAR and photos
Vegetation	LiDAR and photos
Slope Height	GIS and LiDAR
Ditch Effectiveness	LiDAR software. Note: Measured width and depth of ditches and used a relative scale to rate.
Roadway width	GIS and LiDAR
Rockfall History	Evidence in pictures and LiDAR
Aperture	Photos on a relative scale and in field
Fracture Spacing	LiDAR software. Note: had to hand marked the discontinuities. Also measured in person and from photos for relative measures.
Rock Compressive Strength	Taken in field via Schmidt Hammer
Static and Dynamic Stresses	Assumed not to change in an area because traffic patterns were same for whole length of road.
Excavation methods	Assumed the same between all cuts because there was no historical record found saying how rock cuts were constructed
Climate/Presence of water	Assumed same in each study area because of proximity between sites
Annual Freeze/Thaw Days	Online databases from NOAA
Maintenance Frequency	Assumed to be the same, did not find information on individual slopes

5.6 RHRS Procedure

RHRS is a relatively simple method to carry out. Each attribute has four categories that are listed which are a scale of worsening conditions. The method was mostly done on a second field trip to the sites. Most of these attributes can be seen by remote methods, but for a true analysis, an onsite study is preferred.

To do this remotely, the following procedures were followed:

1. In ArcGIS, the area is sectioned off into compartments of a certain width based on a centerline using the TopCat toolbox (Olsen et al., 2012)
2. Calculate the zonal statistics of each compartment on the DEM
3. With this find the height of each slope (the range)
4. Analyze via photos the structural condition, rock friction or differential erosion, rock fall history and block size

5. Measure the ditch widths on LiDAR point clouds
6. Sum ratings to give a RHRS number

The final attribute list can be seen in table 5.2. Several attributes were omitted from the original Pierson system so the maximum possible score was 600.

Table 5.2 Final RHRS Factors (revised from Pierson 1991)

Attribute	Form
Structural Condition	Onsite analysis/Photo analysis
Rock Friction/Differential Erosion	Onsite analysis (This could be assumed by photos, but not accurately)
Ditch Effectiveness	Measured from LiDAR, looked at relative volume. Onsite visit.
Rockfall History	Looked at Talus piles, evidence in photos, onsite
Slope Height	Measured within the LiDAR point cloud
Block Size	Onsite/LiDAR, in Glitter Gulch there is no real "blocks"

5.7 Results of the RHRS

Figures 5.8 and 5.9 are samples of the final rated slopes in compartments of 10 m width. There is a difference between the two areas rated. Glitter Gulch had attribute which dominates with most of the scores ranging between 3 and 27. Not only was there a semi-effective ditch in this area, but the block sizes were much smaller than in Long Lake. In contrast, at Long Lake the slope was the predominate attribute with the score being the highest possible in most compartments colored red along with a high ditch score in all the compartments.

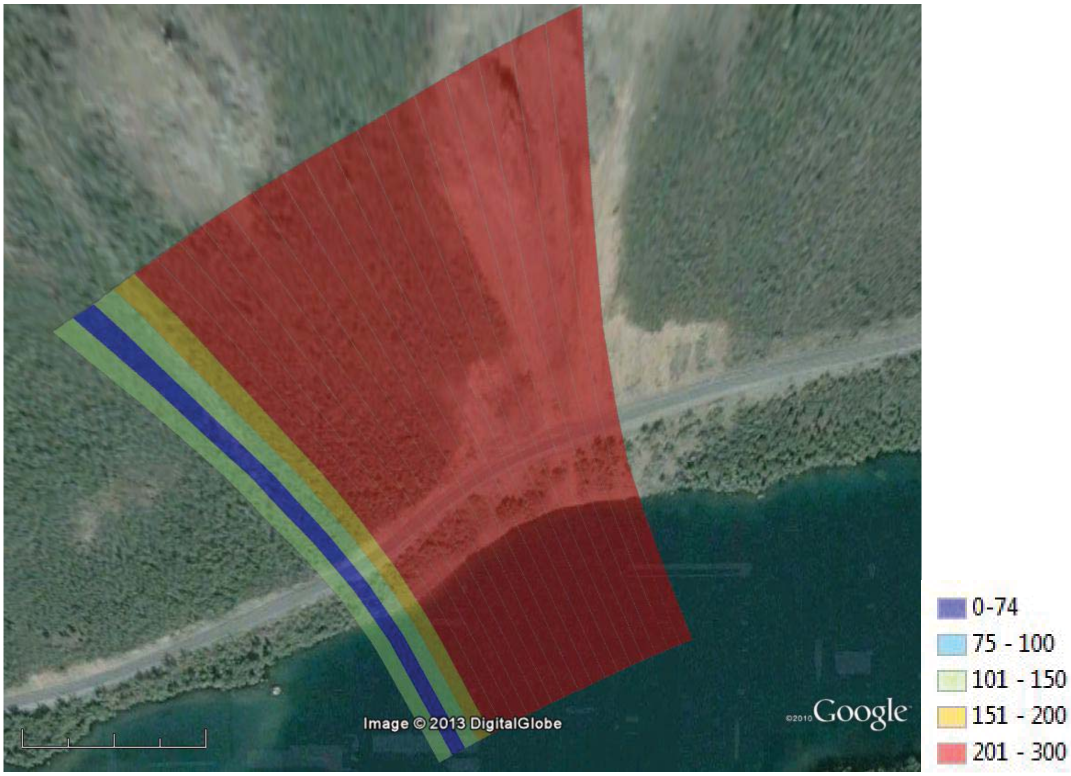

Figure 5.8 Long Lake section scored with RHRS

Figure 5.9 Glitter Gulch section scored with RHRS

5.8 RDA procedure

Note: This method has been used over a limited area and has not yet to implemented across the full length of each site. This work was done before the latest field investigation. A similar but modified process will most likely be used for a final analysis in Phase II.

A DEM file from the LiDAR and other information such as weathering, ability to see where stabilization and protective measures are located are needed to complete this process.

1. Make a fishnet in ArcGIS (Data Management Tools\Feature Class\Create Fishnet)
    i. This can be various sizes depending on what scale you want the final product to be
    ii. Use the option to create polygons with labels
2. Create aspect raster from DEM (Spatial Analyst Tools\Surface\Aspect)
3. With labels layer, extract multi values to points (Spatial Analyst Tools\Extraction\Extract Multi Values to Points)
    i. Use the aspect and the DEM file to get aspect and elevation.
    ii. This will only give the amount at the center of the polygon. Another way is to use zonal statistics for each layer to extract the mean\max\min values.
4. Gather attributes in form that can be easily analyzed (See table 3 for attributes and how to measure)
    i. The easiest forms: Google earth files and shapefiles
    ii. This might require the building of a shapefile or kmz of the needed information
5. Import kmz (a compressed keyhole markup language file used in Google Earth) files into ArcMap
6. Select by location each value
    i. Add a column in the fishnet file for each attribute.
    ii. Give each polygon the attribute rating
7. Identify traces
    i. Find their length
    ii. Join them by location and give each polygon on the fishnet the value of the traces
8. Join the point attributes to the polygon attributes
9. Export data
10. Take the data into excel and calculate RDA
    i. For this an excel spreadsheet was set up with the formulas and calculated the RDA rating for each polygon
11. Save the ID of the polygon and the RDA rating into a .csv file
12. Open .csv file in ArcMap and join to the polygon file
13. Display RDA values
    i. This file will be a flat file, use ArcScene and use the DEM as a base file to better visualize
    ii. Export as KMZ file into Google Earth

Table 5.3 Final RDA Factors (Nicholson 2004)

Attribute	Form
Fracture Spacing	Manually traced discontinuities and imported into ArcMap
Fracture Aperture	Gave traced discontinuities a relative scale (This was done before the second field investigation)
Rock Compressive Strength	Assumed to be the same (in the next iteration field measurements will be used)
Rock Material Weathering Grade	Created a kmz file with areas of relative weathering
Altitude	Used DEM elevation
Aspect	Derived an aspect map from DEM
Groundwater and Surface Runoff	Assumed to be the same for all cases
Static Stresses	Assumed to be the same for all cases
Dynamic Stresses	Assumed to be the same for all cases
Excavation History	Assumed to be the same for all cases
Stabilization and Protective Measures	Created a kmz file with stabilization and protective features
Vegetation Cover	Created a kmz file outlining the vegetation on the slopes
Slope Geometry	Measured slope
Rock Mass Structure	Calculated from other attribute measurements
Time Since Excavation	Assumed to be the same for all cases
Direct disturbance	Assumed to be the same for all cases

5.9 Results of the RDA

Figure 5.10 represents a 3 meter by 3 meter grid of the RDA in Glitter Gulch area. The areas of purple and blue represent the high likelihood of failure and follow the discontinuities. This is one issue that was found with this implementation as the discontinuities were hand traced and if a discontinuity was missed or skipped, the results will be skewed.

Note: This method has yet to be implemented on the whole area. Figures 5.8and 5.9 are examples of the rated product.

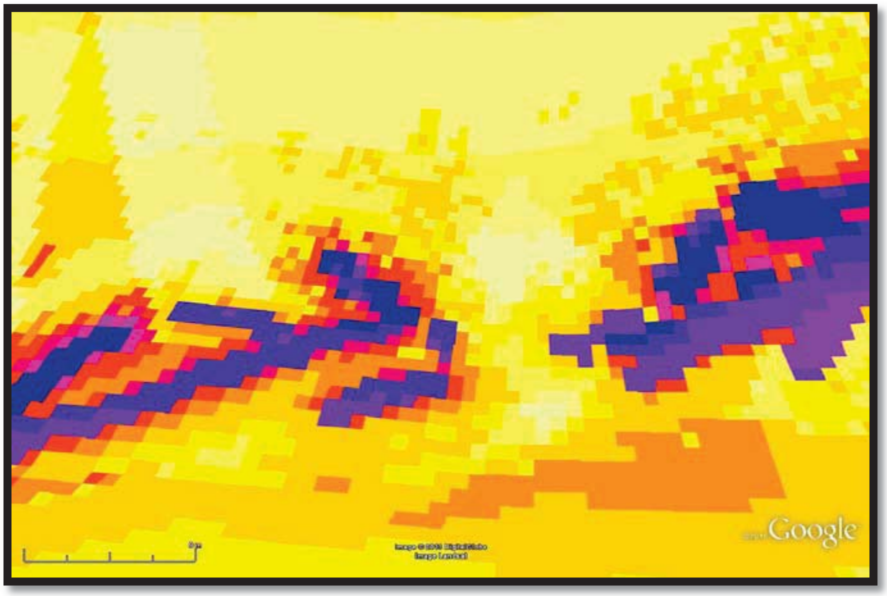

Figure 5.10 RDA rating on section in Glitter Gulch

5.10 <u>Discussion of classification methods</u>

Using classifications systems that are meant for onsite evaluations with remote data can be done, but the information has to be supplemented with onsite field work. These systems are adequate for their intended use, but used remotely they are cumbersome and do not take full advantage of technological advances.

5.10.1 *Use of LiDAR with Classification systems*

Both systems had attributes that were easy to extract from LiDAR and ones that were difficult. The main problem with the systems was how to interpret LiDAR data into categorical information. Much of the process had to be accomplished by hand because of the need to interpret these categories. Examining these classification systems has helped to understand what processes are important and how to examine LiDAR data to interpret these attributes. But LiDAR is more powerful when it is not constrained to current classification systems.

5.10.2 *Contributing Attributes*

Sometimes there are one or two factors that drive a system. These contributing attributes are important to understanding and predicting slope stability. Both RHRS and RDA use a partially categorical approach to look at factors which sometimes overlooks the importance of these contributing attributes. Structural condition is one such factor that while there are several choices, many slopes examined onsite did not fit neatly into any one category. Instead attributes that might be main contributors were lumped into a category that might not show their significance.

One contributing factor, overhang is not considered in the RHRS system and not an important factor in RDA. This is one of the main factors in Glitter Gulch's geologic development. Through LiDAR this can be measured to know the approximate volume of these overhangs and allow for a foreknowledge of how much material potentially might be falling from a slope.

5.10.3 *Conclusions on Classification Systems*

Classification systems have their place, but as technology advances, a better picture can be seen through the use of emerging technology such as LiDAR for better understanding of the processes and to better protect assets and the safety of users. RHRS and RDA have given us a foundation to understand rock slope processes that will now be built upon in our upcoming research.

5.11 Continuing work with LiDAR and attributes

LiDAR technology can capture much more than can be categorized with a simple classification system. With the ability to give a snap shot of time, LiDAR can be compared to snapshots taken in the future to understand the most significant factors for slope failure. We suggest several morphological features to track and understand slope cuts. Some examples are slope of hillside, volume of overhang, strike and dip, and roughness. Each of these can be measured with LiDAR and compared to the time series data that is being collected to see how it impacts stability. Once these are understood, a system will be developed to use LiDAR scans to help DOTs inventory their geological assets allowing them to know the potential for failure for individual sites for mitigation purposes.

5.12 Risk Assessment

The probability of slope instability or landslide can be expressed by the term $P(H_i)$ in the above equation refers to a probability density function that represents the likelihood of landslides of various magnitudes. This implies that landslides conform to a random process. Whether or not slope failures conform to a random process is debatable. However, previous work has used this representation for convenience in addressing the uncertainties associated with landslide magnitudes. To formulate such a representation requires considerable historical information for statistics as well as analytical modeling; the results of which are still questionable.

In the context of this study the probability of *any* rock-slope failure event will be considered. Assembling an adequate database or analytical modeling is well beyond the scope of what can be accomplished here. In addition, to enhance the utility of this project the researchers will, to the greatest extent possible, maintain the use of existing AKDOT&PF slope assessment policy including rating methodology. While not practical to determine an appropriate probability distribution, it is possible to introduce the likelihood of a landslide a *measure of belief* based on experience or some a priori knowledge of the slope. The measure-of-belief approach will be used here as the axioms of probability theory are still applicable. The $P(H_i)$ term now becomes $P(H)$. For the purposes of this study the latter term represents:

The probability, as a measure of belief, that any rock fall will occur within some timeframe

For the purposes of this study the "timeframe" will remain undefined. The temporal aspect of slope deterioration or landslide frequency is very difficult to address. Not being able to substantiate a timeframe associated with landslide events, the probability will be resolved to: *The probability, as a measure of belief, that any rock fall will occur given the present condition of the rock slope.*

In the context of probability theory, the probability term is more correctly written as $P(H|CR)$. That is, *the probability of a rock fall (of any magnitude) given the present Condition Rating*.

Consider the table in Figure 2.3.1. The Category Rating numerical values can be found in the literature for at least the past twenty years. The significance of this number is not apparent as it has no physical meaning; i.e., no physical units associated with them. They are interpreted to represent an increasing severity of hazard with increasing numerical value. Observing that the category rating is $CR = 3^x$ for x=1, 2, 3, 4 it is presumed that system is intended to make the most hazardous conditions obviously distinct from less hazardous conditions. To facilitate the risk assessment of a slope using an in-place rating system, the Category Rating scheme will be mapped to a scale of 0 to 1. The mapped values shall be construed as a relative measure of belief for the likelihood of a slope failure within some (as yet unspecified) timeframe. Figure 2.3.2 illustrates this mapping for a single field of the proposed slope hazard rating system.

Huang, Darrow and Calvin (2009) indicate that, for rock slopes, the largest composite score is 729; corresponding to nine fields with a score of 81. Extending the discussion above to a composite score yields.

Chapter 6 Discussion

A long-term concern of highway managers is unstable slopes (i.e., landslides) along transportation corridors. Instabilities create safety risks and impact regional commerce, even if events occur infrequently. The infrequency of slope movement is a factor that often results in complacency, especially with respect to budgeting for preventative solutions. Coupled with laborious and costly monitoring of slopes over time, it is understandable that most decision support systems (DSS) that drive proactive transportation asset management (TAM) initiatives have not been implemented.

Current landslide inventory systems require significant time to develop and generally provide only basic information after a collapse has occurred. As such, they do not provide an understanding of how risk varies with time and location. A proactive, near-automated approach for the identification of slope instability offers the potential of reduce overall operation and repair costs while reducing economic consequences of interrupted transportation and commerce, while additionally enhancing public safety.

Remote sensing technology, such as lidar (light detection and ranging) laser scanning, shows promise for the rapid assessment of linearly distributed infrastructure systems, such as highways. Time-series lidar datasets enable a higher level of asset management confidence than current probabilistic studies based on landslide inventories.

The scope of this project includes the development of <u>qualitative</u> relative risk model for slope stability assessment using terrain models created from lidar data. In the second phase of the work, we will focus on <u>quantitative</u> time-series analysis using lidar data and integrating this information into the model developed in the first phase of research and into an agency's transportation asset/performance management program.

The major findings of this first phase of research include the following:

1. Static and mobile static terrestrial lidar systems improves the acquisition of repeatable data sets with a higher quality than mobile terrestrial lidar systems mounted on a vehicle traveling at highway speeds. This is because the static configuration on a tripod or tripod mounted on wagon requires the operator to consider optimal locations to collect scan data, including scans from multiple angles.
2. However, static platforms are much less efficient than mobile platforms and are not realistic to apply across an entire state (particularly a state as large as Alaska). An appropriate strategy would be to use mobile lidar along all sections of highway routinely complemented by static lidar acquisitions in areas that show the highest levels of slope degradation or have been identified previously as highly unstable.
3. The collection of high resolution imagery to render the lidar point cloud in real colors greatly assists in the interpretation of geologic features that cannot be identified solely based on lidar point cloud morphology. Thus a camera acquisition should be integrated with the lidar scanner. Moreover, care should be taken to ensure appropriate exposure thresholds are used on the acquired imagery.
4. There is always some amount of data "scrubbing" (data editing) with the lidar point cloud required. For example, transient features such as passing cars and people appear in the data. Certain atmospheric conditions create lidar artifacts that should be removed. Perhaps most importantly, vegetation such as tufts of

grass and tree saplings on a talus slope can create noise obscuring the slope characteristic behind the vegetation.

5. Most current automated ground filters are currently not well-suited to handle mobile (or static) lidar data because of high variability in point density and steep slopes. Hence, a significant amount of manual editing is required.

Finally, the qualitative risk analysis conducted in this first phase is precisely that – an approximation of landslide risk. True probabilistic risk analysis will require a quantitative analysis that can only be modeled with repeated collection of slope data using the lessons learned in this phase one project.

Chapter 7 Conclusions and Recommendations

The goal of the PacTrans Phase One project is to develop a qualitative relative risk model for slope stability assessment using terrain models created from MLS data. Phase Two will focus on a quantitative, time-series analysis using MLS data and integrating this information into the qualitative model developed in the Phase One.

The quantitative and qualitative risk modeling enable administrators to asses slope assets along highway corridors and evaluate risks. This work-flow will identify the susceptibility of a slope to failure, using GIS-based data and state-of-the-art mobile mapping technologies, providing a virtual 3D digital corridor map in unprecedented detail. Information regarding the likelihood of slope failure will be coupled with the volume of service experienced by the roadway/corridor to produce a risk-based decision tool that facilitates diligent programming of slope management measures based on risk to the customer (i.e., risk of failure). This platform would be critical to property inspections and expenditure based on risk. Such a tool would be invaluable to administrators tasked with managing a corridor slope inventory. This effort would be tied into an agency's transportation asset\performance management program.

The aim of this project aligns with the strategic goals of **Safety, Cost Effectiveness,** and **Good Repair**. Slope failures (e.g., landslides) pose a significant hazard to public safety, particularly when they occur near public infrastructure. The debris from failed slopes can not only create impact hazards but can also close down sections of highway for extended periods of time. This is particularly problematic when these incidents occur along critical lifeline corridors during emergency conditions. Several highway corridors cross unstable terrain in the Coast Range of the Pacific Northwest and in many parts of Alaska, providing minimal alternatives for people to re-route in the event of a road closure. A proactive, performance-based approach to monitor slopes prior to catastrophic failure will enable improved decisions regarding appropriate maintenance repair and mitigation and will ensure improved allocation of the limited DOT resources.

This project also ties significantly into the MAP21 national performance goals: Safety, Infrastructure Condition, Congestion Reduction, System Reliability, Freight Movement and Economic Vitality, Environmental Sustainability, Reduced Project Delivery Delays. A key focus of the MAP21 legislation calls for use of advanced geospatial technologies to aid in asset management by transportation agencies.

7.1 Phase Two Recommendations

This research effort will focus on continual slope monitoring and changes through time-series scans of key corridors. Steps in the proposed methodology include:

Task 1: Acquire time series (2-3), high resolution MLS datasets for 3-4 corridor sections (approximately 3-5 miles in length) at the Phase 1 study corridors. At key locations, higher accuracy static laser scans will also be obtained for validation purposes. These scans will be collected again for locations surveyed in Alaska as well as location in Oregon. (Oregon DOT has already collected some baseline mobile scans throughout the state they are willing to provide to the project team). Oregon DOT will also acquire repeat scans in those areas. We will then process these data following a similar procedure used in Phase I. We will also seek out additional information such as geology, rainfall, groundwater levels, land cover, etc. for further correlation.

a. Develop virtual, 3-D map of corridor
b. Clean and filter data to remove noise
c. Compare data (and potentially merge) with airborne laser scan data of region
d. Classify ground points
e. Generate a Digital Terrain Model (DTM) for input into GIS
f. Perform QA/QC on the DTMs
g. Generate slope, curvature, and terrain roughness maps in GIS
h. Perform quantitative change analysis between surveys
i. Time permitting, extract feature layers (exposed soil layers in rock outcrops) using LIDAR intensity values and photographs integrated with the scan dataset.
j. Correlate with other geospatial datasets

Task 2: Develop customized algorithms to automatically generate and extract statistics for geometric metrics such as slope angle, terrain roughness, curvature, and other easily detectible features relevant to slope stability. This will also include development of improved ground surface versus vegetation filtering techniques necessary to create accurate terrain models. Existing methodologies developed for airborne LiDAR datasets do not work well for MLS data due to the different look angle and features of interest. Hence, they tend to remove features of interest on the cliff face, which are vital to our assessment. This differs from Phase I as we will develop automated procedures to simplify many of the manual procedures completed in Phase I as we focused on developing a methodology.

We will then further develop and modify a tool (TopCAT – Topographical Compartment Analysis Tools, Olsen et al. 2012) created by Co-PI Olsen (original designed for coastlines) to discretize the highway into smaller segments. Currently, this tool is only capable of change comparison between epochs. However, we will modify it to extract parameters such as slope, curvature (both plan and profile), roughness metrics, and aspect. We will then create a module in the tool to perform a stability analysis using these input parameters extracted from the various surface modules.

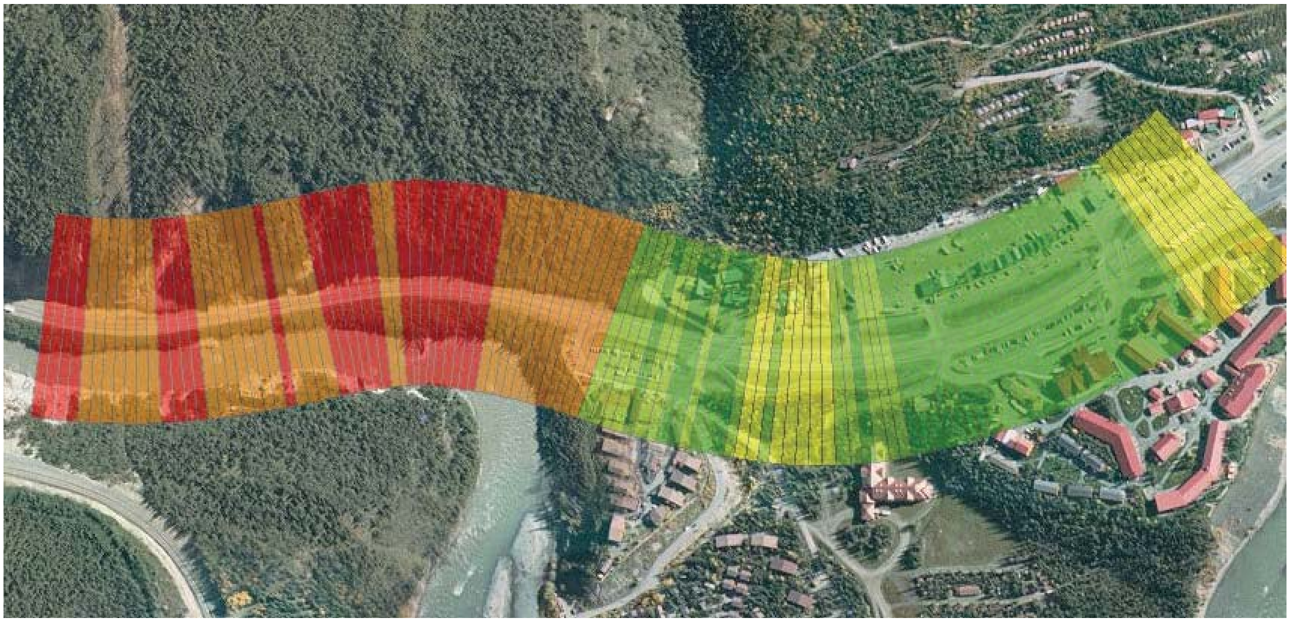

Figure 7.1 Example potential output highlighting areas (10 m sections) along a highway of highest potential landslide or rockfall risk. Note that this figure is based a simple model using only one parameter, slope. The quantitative change analysis results combined with the risk from Phase II will enable us to create much more accurate and reliable highway risk map.

Task 3: Evaluate change detection capabilities of MLS. These observed changes\movements will be statistically compared to the parameters evaluated in (2) to improve the developed model.

Task 4: Create a "best practices" document for acquisition and processing of MLS data for slope stability analysis. Given the variety of uses for MLS data, this document will consider other likely uses for the data.

Task 5: Develop a models to relate sediment mobilization rates (i.e., erosion volume) to surface morphology indices. In Phase 2 of the project, we will rely on the change detection data from Task 3 to move beyond to current qualitative measures of slope hazard (high, moderate, low) to direct quantitative measure of sediment mobilization rates (i.e., volume/surface area/ year). Specifically, we will derive detailed measures of annualized slope erosion for each category of rock based from the available LiDAR surveys. Here, "rock category" refers to classes of rock slope that share common structural features (e.g., condition and geometric orientation—strike, dip, persistence, and spacing—of key discontinuity sets), and a similar degradation (or weathering) index, which is related to rock type.

These models will be presented before the geotechnical (and geotechnical asset management) community through conversations with PNW DOTs, conference presentations, and peer-review of resulting publications. It is critical to note that the intent is not to replace detailed site investigations at unstable sites that require geotechnical analysis and testing. Rather, the intent is to provide guidance as to where the most likely unstable sites are located as well as provide an overview picture of stability along the entire transportation system, enabling a transportation agency to quickly and reliably extract metrics for use in a performance based transportation asset management program. This approach will empower the transportation agency to optimally allocate limited resources.

Comparisons of the sites in Alaska, Oregon, and possibly Washington will enable us to test the robustness of the approach in areas with different weather and environmental conditions.

Task 6: Create an assessment tool that will quantify slope-stability risk-levels along corridors. This will build on the tool created in Task 2, but will populate each compartment with a risk level and other information useful to highway asset management personnel. The intent will be to provide a tool that is simple to implement and provides visual results that are easy to interpret but also performs powerful analysis behind the scenes. As an example, we performed a simulated example using only one parameter slope for the Glitter Gulch section. Ideally such a tool could be expanded to include other assets\features in the future to create detailed condition maps for entire corridor ROWs.

Task 7: Disseminate results in publications, including a final report, journal papers and conference presentations. Potential targets for dissemination are discussed in Section 5.

7.2 Expected Benefits and Conclusions

As a result of this project, DOTs will be able to make predictions of the likelihood of slope failure and resulting socio-economic impact, thereby allowing proactive planning and execution of slope remediation projects. This objective approach will allow effective communication of transportation infrastructure budget impacts to decision makers including DOTs, legislatures, and state executives. The platform will be a tool for objectively identifying which rock slopes pose the greatest risk to a transportation corridor and the customers that use it – thereby indicating where limited resources may have the greatest benefit to a highway corridor, and transportation system as a whole. Proactive slope remediation allows for a cost-effective approach, but more importantly, is a means to mitigate life-safety concerns posed by slope failures. Thus, the public, as both user and taxpayer, will benefit from this project.

The end product envisioned for this project will be a detailed methodology and necessary tools in which a DOT could take the output from a geo-referenced MLS survey (e.g., las file) and semi-automatically generate products such as a terrain model, slope map, curvature map, slope stability analysis map (e.g. RDA), change\deformation analysis map, etc. with minimal input from the end-user. These products would be created in formats that can be read into common DOT software such as Microstation and GIS.

The findings of this research and training for the product will be transferred through presentations given in meetings and workshops with DOT personnel. Findings will be summarized in technical reports, conference proceedings, and journal papers. The research team will work closely with Geotechnical and Geomatics personnel within each participating DOT to ensure that the results will feed into their current efforts and workflows. This research will enable a DOT to efficiently and safely manage unstable highway slopes, including:

1. Improved information regarding impending hazards to lifeline corridors in the Pacific Northwest.
2. Proactive assessment of slope stability to determine areas of greatest risk prior to catastrophic consequences.

3. A simplified procedure and easy to use tools to analyze MLS data quickly for slope assessments and prioritize potential problem areas.
4. Mobile LiDAR data that can be used for other applications throughout any transportation organization.

References

Chapter 8 References

American Association of State Highway and Transportation Officials (AASHTO). 1997. "Segregation: causes and cures for hot mix asphalt." Publication by the Joint Task Force on Segregation of AASHTO Subcommittees on Construction and Materials, and National Asphalt Pavement Association, Washington, D.C.

Amirkhanian, Serji N., and Bradley J. Putman. 2006. "Laboratory and field investigation of temperature differential in HMA mixtures using an infrared camera." Report No. FHWA-SC-06-06, Clemson University, Clemson, SC.

Baltsavias, E.P. (1999). "Airborne laser scanning: basic relations and formulas," ISPRS Journal of Photogrammetry & Remote Sensing, Vol. 54: 199–214

Barton, N., Lien, R., & Lunde, J. (1974). Engineering classifications of rock masses for the design of tunnel support. *Rock mechanics (Vol 6)*, 189-236.

Bedford and Cooke. 2001. Probabilistic Risk Analysis: Foundations and Methods. Tim Bedford and Roger Cooke. Cambridge University Press. Cambridge, United Kingdom. 2001Belowich, Michael A. Matanuska Coal Field. Field Guide, Anchorage Alaska: Alaska geological Society, 2006.

Belowich, Michael A. Matanuska Coal Field. Field Guide, Anchorage Alaska: Alaska geological Society, 2006.

Bieniawski, Z. T. (1973). Engineering classification of jointed rock masses. *Transactions of the South African Institution of Civil Engineers 15(12)*, 335-344.

Berti, M., Corsini, A., Daehne, A., 2013. Comparative analysis of surface roughness algorithms for the identification of active landslides. Geomorphology 182, 1–18.

Bitenc, M.; Lindenbergh, R.; Khoshelham, K.; van Waarden, A.P. Evaluation of a LIDAR land-based mobile mapping system for monitoring sandy coasts. Remote Sens. 2011, 3, 1472–1491.

Brock, J. Don. 1986. "Segregation of Asphaltic mixtures." Proceedings of the Association of Asphalt Paving Technologists, 55: 269-277.

Brenner, C., (2009). "Extraction of features from mobile laser scanning data for future driver assistance systems." Advances in GIScience : 25–42.

Brown, O.W. and Hugenholtz, C.H., (2013). Quantifying the effects of terrestrial laser scanner settings and survey configuration on land surface roughness measurement Geosphere, April 2013, v. 9, p. 367-377, First published on March 18, 2013, doi:10.1130/GES00809.1

Burns, S.; Jones, W.S. Capturing the Road of Tomorrow—UDOT's Transportation Asset and Highway Safety Data Program 2012; Geospatial Transportation Mapping Association Webinar.

Burns, W.J., and Madin, I.A. (2009). "Protocol for inventory mapping of landslide deposits from light detection and ranging (LiDAR) imagery," DOGAMI Special paper 42.

California Department of Transportation. Chapter 15, Terrestrial Laser Scanning Specifications. In Surveys Manual; Publisher: CalDOT, Sacramento, CA, USA, 2011.

Chang, J.C.; Tsai, M.K.; Findley, D.J.; Cunningham, C.M. Infrastructure Investment Protection with LiDAR; The National Academics: Washington, WA, USA, 2012.

Chang, J.C., D.J. Findley, M.K. Tsai,and C.M. Cunningham (2012).Infrastructure Investment Protection with LiDAR. North Carolina Department of Transportation Research Project No. 2012-15

Connor, Cathy, and Daniel O'Haire. Roadside Geology of Alaska. Missoula: Mountain Press Publishing Company, 1988.

CTC & Associates. LIDAR Applications for Transportation Agencies; WisDOT Research Report: Madison, Wi, USA; 2010. Available online: http://www.wisdotresearch.wi.gov/wp-content/uploads/tsrlidarapplications1.pdf (accessed on 12 July 2011).

Deere, D. U., & Deere, D. W. (1988). *The Rock Quality Designation (RDQ) Index in Practice.* Philadelphia: American Society for Testing Materials.

Duffell, C.G.; Rudrum, D.M. Remote Sensing Techniques for Highway Earthworks Assessment. In Proceedings of GeoFrontiers 2005, Austin, TX, USA, 24–26 January 2005; pp. 1–13.

Fardin, N., Feng, Q., and Stephansson, O., 2004, Application of a new in situ 3D laser scanner to study the scale effect on the rock joint surface

roughness: International Journal of Rock Mechanics and Mining Sciences, v. 41, p. 329–335, doi:10.1016/S1365-1609(03)00111-4.

Frankel, K. L., and J. F. Dolan (2007), Characterizing arid region alluvial fan surface roughness with airborne laser swath mapping digital topographic data, J. Geophys. Res., 112, F02025, doi:10.1029/2006JF000644.

Frankel. 1988. Frankel, Ernest G. System Reliability and Risk Analysis. 2nd ed. Kluwer Academic Publishers. Boston, MA. 1988.

Glennie, C. Kinematic terrestrial light-detection and ranging system for scanning. Transp. Res. Rec. 2009, 2105, 135–141.

Glennie, C. Reign of point clouds. A kinematic terrestrial LIDAR scanning system. Inside GNSS 2007, 2, 22–31.

Glennie, C. Rigorous 3D error analysis of kinematic scanning LIDAR systems. J. Appl. Geod. 2007, 1, 147–157.

Gong, J.; Zhou, H.; Gordon, C.; Jalayer, M. Mobile Terrestrial Laser Scanning for Highway Inventory Data Collection. In Computing in Civil Engineering (2012); pp. 545–552.Goudie, Andrew S. "The Schmidt Hammer in geomorphological research." Progress in Physical Geography, 2006: 703-718.

Hani, A.F.M., Sathyamoorthy, D., Asirvadam, V.S., 2011. A method for computation of surface roughness of digital elevation model terrains via multiscale analysis. Computers & Geosciences 37, 177–192.

Harp, E. and Noble, M. (1993) An engineering rock classification to evaluate seismic rock-fall susceptibility and its application to the Wasatch Front, Bulletin of the Association of Engineering Geologists Vol. 30, 3, 293-319

Hiremagalur, J.; Yen, K.S.; Akin, K.; Bui, T.; Lasky, T.A.; Ravani, B. Creating Standards and Specifications for the Use of Laser Scanning in Caltrans Projects. AHMCT Rept.# UCD-ARR-07–06–30–01, Davis 2007.

Hofmeister, J. et al. (2000) Earthquake-induced slope instability: methodology of relative hazard mapping of the Salem Hills, Marion Country, Oregon, Oregon Dept. of Geology and Mineral Industries.

Hoek, E., & Brown, E. T. (1997). Practical estimates of rock mass strength. *International Journal of Rock mechanics and Mining Sciences 34(8)*, 1165-1186.

Hudson, Haas and Uddin. (1997). Infrastructure Management: Design, Construction, Maintenance, Rehabilitation, Renovation. McGraw Hill, New York, New York.Huang, Scott L., Margaret M. Darrow, and Peter Calvin. 2009. “Unstable Slope Management Program - Background Research and Program Inception”. Project Report, Alaska Department of Transportation and Public Facilities.

Hults, Chad P., Denny L. Capps, and Phil F. Brease. Field Guid to the Geology of the Denali National Park Road and the Parks Highway from Cantwell to Healy. Filed Trip, Alaska: Alaska Geological Society, 2013.

Iwahashi, Junko, and Richard J. Pike. 2007. “Automated classifiations of topography from DEMS by an unsupervised nested-means algorithm and three-part geometric signature.” Geomorphology 86, 209-440

Jaboyedoff, M., Oppikofer, T, Abellan, A., Derron, M.H., Loye, A., Metzger, R., Pedrazzini, A. 2010.“Use of LiDAR in landslide investigations: a review,” Natural Hazards.

Jaselskis, E.J.; Gao, Z.; Welch, A.; O’Brien, D. Pilot Study on Laser Scanning Technology for Transportation Projects. In Proceedings of the 2003 Mid-Continent Transportation Research Symposium, 2003.

Kaplan and Garrick. 1981. “On the Quantitative Definition of Risk”. Stanley Kaplan and B. John Garrrick.Risk Analysis, Vol. 1, No. 1.Society for Risk Analysis. 1981

Kayen, R., Stewart, J.P., Collins, B. (2010). “Recent advances in terrestrial LiDAR applications in geotechnical earthquake engineering,” Proc. 5th Int. Conf. on Recent Advances in Geotech. Earthquake Engrg and Soil Dynamics, ASCE.

Keefer, D. K.: The susceptibility of rock slopes to earthquake-induced failure, Bulletin of the Association of Engineering Geologists,30, 353–361, 1993.

Kelman. 2003. “Defining Risk”. IlanKelman.FloodRiskNet Newsletter, Issue 2. Winter, 2003.

Kemeny, J. Application of Three-Dimensional Laser Scanning for the Identification, Evaluation, and Management of Unstable Highway Slopes; In Transportation Pooled Fund Project TPF-5(166) Final Report; Washington, DC, USA, 2013.

Kemeny, J. et al. (Unpublished Report). “Application of Three-Dimensional Laser Scanning for the Identification, Evaluation, and Management of Unstable Highway Slopes,” http://www.pooledfund.org/Details/Study/391

Kemeny, J., and Turner, A.K., (2008) “Ground-based LiDAR Rock slope mapping and assessment,” Publication No. FHWA-CFL/TD-08-006.

Kemeny, J., Norton, B., Handy, J., and Donovan, J. (2008). “Three-dimensional digital imaging for the identification, evaluation and management of unstable highway slopes,” Final Report for Highway IDEA project 119, TRB NAS.

Lato, M.; Hutchinson, J.; Diederichs, M.; Ball, D.; Harrap, R. Engineering monitoring of rockfall hazards along transportation corridors: using mobile terrestrial LiDAR. Nat. Hazards Earth Syst. Sci. 2009, 9, 935–946.

Lee and Jones 2004 (chapter 2 page 44)

Mavrouli, O., Corominas, J., and Wartman, J. (2009) "Methodology to evaluate rock slope stability under seismic conditions at Solá de Santa Coloma, Andorra," Natural Hazards and Earth System Science, Vol. 9, pp.1763-1773.

Metzger, A. T., (2008). "Technical Report TR-6-072-OCN: Mission-risk Based Work Prioritization for Navy-owned Bridges, Water Tanks, and Waterfront Structures". Prepared for Commander, Naval Facilities Command, Atlantic. August 31, 2008. Washington Navy Yard, Washington, D.C.

Miller, P.; Mills, J.; Barr, S.; Lim, M.; Barber, D.; Parkin, G.; Clarke, B.; Glendinning, S.; Hall, J. Terrestrial laser scanning for assessing the risk of slope instability along transport corridors. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 2008, 37, 495–500.

Moddares, Kaminski and Krivtsov 1999 (chapter 2 page 44)

Pierson, Lawrence A. 1991. "Rockfall Hazard Rating System". Washington, DC: Federal Highway Administration.

Nicolson, Dawn T. 2004. "Introduction to the RDA (Rockslope Deterioration Assessment". Publshed at: http://www.dawntnicholson.org.uk/. Accessed 10/9/2013

Nicolson, Dawn T. 2005a. "RDA Stage One". Published at: http://www.dawntnicholson.org.uk/. Accessed 10/9/2013

Nicolson, Dawn T. 2005b. "Hazard assessment for progressive, weathering-related breakdown of excavated rockslopes." Quarterly Journal of Engineering Geology and Hydrogeology, 37, 327–346.

Olsen, M.J. *In-situ* change analysis and monitoring through terrestrial laser scanning. *J. Comput. Civ. Eng.* **In Press.**

Olsen, M.J., Butcher, S., and Silvia, E.P., (2012). Real-time change and damage detection of landslides and other earth movements threatening public infrastructure, OTREC Final Report 2011-22 and ODOT Final Report RS 500-500, 80p.

Olsen, M.J., Roe, G.V., and Raugust, J. (2013b, In Press). Use of advanced geospatial data tools, technologies, and Information in DOT projects, NCHRP Synthesis 446, Topic 43-09, 144 pp.

Olsen, M.J.; Johnstone, E.; Driscoll, N.; Ashford, S.A.; Kuester, F. Terrestrial laser scanning of extended cliff sections in dynamic environments: Parameter analysis. *J. Surv. Eng.* **2009**, *135*, 161–169.

Olsen, M.J.; Roe, G.V.; Glennie, C.; Persi, F.; Reedy, M.; Hurwitz, D.; Williams, K.; Tuss, H.; Squellati, A.; Knodler, M. *Guidelines for the Use of Mobile LIDAR in Transportation*

Applications; TRB NCHRP Final Report 748; Publisher: TRB Washington, DC, USA, **2013**.

Olsen, M.J., Young, A.P, & Ashford, S.A. (2012).“TopCAT – Topographical Compartment Analysis tools for ArcGIS®” Computers and Geosciences, 45, 284-292.

Olsen, M.J.; Singh, R.; Williams, K.; Chin, A. Transportation Applications Subchapter. In Manual of Airborne Topographic Lidar; Publisher: ASPRS Bethesda, MD, USA, 2012.

Olsen, Michael J., Adam P. Young, and A Scott Ashford. "TopCAT - Topographical Compartment Analysis Tool to analyze seacliff and beach change in GIS." Computers and Geoscience 45, 2012: 284-292.

Palmstrom, A. (1995). RMi - A system for characterizing rock mass strength for use in rock engineering. *Journal of Rock Mechanics and Tunneling Technology, 1(2)*, 69-108.

Pierson, Lawrence A. Rockfall Hazard Rating System. Washington, DC: Federal Highway Adminsitration, 1991.

Pollyea and Fairley (2011). Estimating surface roughness of terrestrial laser scan data using orthogonal distance regression, Geology, 39(7), p.623-626.

Puente, I.; González-Jorge, H.; Martínez-Sánchez, J.; Arias, P. Review of mobile mapping and surveying technologies. Measurement 2013, 47, 2127–2145.

Puttonen, E.; Lehtomäki, M.; Kaartinen, H.; Zhu, L.; Kukko, A.; Jaakkola, A. Improved sampling for terrestrial and mobile laser scanner point cloud data. Remote Sens. 2013, 5, 1754–1773.

Rausand and Høyland, 2004 (chapter 2 page 44)

Romana, M. (1985). New adjustment ratings for application of Bieniawski classification to slopes. *International Symposium on the Role of Rock Mechanics*, 49-53.

Schulz, W.H. (2005) “Landslide susceptibility revealed by LiDAR imagery and historical records,” USGS Open File Rep. 2005-1405.

Silvia, E.P., & Olsen M.J. (2012). “To Level or Not to Level: laser scan inclination sensor evaluation,” Journal of Surveying Engineering, 138(3), 117 -125.

Singh, R. (2008). Engineering Automation, Key Concepts for a 25 Year Time

Horizon,Vol. 3, Oregon Department of Transportation report. Available at: http://www.oregon.gov/ODOT/HWY/GEOMETRONICS/docs/dozer/engineering_automation-key_concepts-8mar2009. pdf.

Schwarz, K.P.; Chapman, M.A.; Cannon, M.W.; Gong, P. An integrated INS/GPS approach to the georeferencing of remotely sensed data. Photogramm. Eng. Remote Sens. 1993, 59, 1667–1674.

Singh, R. Engineering Automation, Key Concepts for a 25 Year Time Horizon; V3, ODOT report, Salem, OR, USA 2008.

Singh, R., Olsen, M.J., and Roe, G.V. (2012). Mobile LIDAR: Theory to Practice 2012; ASCE workshop course notes.

Su, Y.Y.; Hashash, Y.M.A.; Liu, L.Y. Integration of construction as-built data via laser scanning with geotechnical monitoring of urban excavation. J. Constr. Eng. Manag. 2006, 132, 1234–1241.

Singh, Bhawani and R.K.Goel. 2011. "Engineering Rock Mass Classification – Tunneling, Foundations, and Landslides." Oxford, UK.

Stanley, Dave. Asset Management in a World of Dirt. TR News 277, November – December 2011.

Thornberry-Ehrlich, Trista. Denali national Park and Preserve: Geologic Resources Inventory Report. Natural Resource Report, Denver Colorado: National Parks Service, 2010.

TRB. 2009. "NCHRP Report 632: An Asset-Management Framework for the Interstate Highway System". Transportation research Board, Washington, D.C.

Trop, Jeffrey M., and Thomas L. Plawman. Bedrock geology of the Glenn Highway from Anchorage to Sheep Mountain, Alaska: Mesozoic-Cenozoic forearc basin development along an accretionary convergent margin. Field Guide, Anchorage Alaska: Alaska Geologic Society, 2006.

Turner, A.K., Kemeny, J., Slob, S., and Hack R., (2006). "Evaluation and management of unstable rock slopes by 3-d laser scanning," Proceedings of IAEG2006.

Vaaja, M.; Hyyppä, J.; Kukko, A.; Kaartinen, H.; Hyyppä, H.; Alho, P. Mapping topography changes and elevation accuracies using a mobile laser scanner. Remote Sens. 2011, 3, 587–600.

Vessely, M. (2013). "Risk-based methods for management of geotechnical features in transportation infrastructure," Proc. ASCE GeoCongress 2013.

Vincent, R.; Ecker, M. Light Detection and Ranging (LIDAR) Technology Evaluation; Missouri Department of Transportation: Kansas City, MO, USA, 2010.

Vosselman, G.; Maas, H.G. Airborne and Terrestrial Laser Scanning; Whittles: Dunbeath, Caithness, Scotland KW6 6EG, UK, 2010.

Wahrhaftig, Clyde, and Robert F. Black. "Engineering Geology along part of the Alaska Railroad." Geological Survey Professional Paper 293, 1958: 71-116.

Western Regional Climate Center, Last Visited November 30, 2013, http://www.wrcc.dri.edu/summary/Climsmak.html.

Williams, K., Olsen, M.J., and Chin, A. (2012). “Accuracy assessment of geo-referencing methodologies for terrestrial laser scan surveys,” Proceedings of the ASPRS annual conference, Sacramento, CA.

Williams, K., Olsen, M.J., Roe, G.V., and Glennie, C., (2013). “Synthesis of Transportation Applications of Mobile LIDAR,” Remote Sensing, Special Issue on Advances in Mobile Laser Scanning and Mobile Mapping, 5(9), 4652 - 4692.

Yen, K.S.; Akin, K.; Lofton, A.; Ravani, B.; Lasky, T.A. Using mobile laser scanning to produce digital terrain models of pavement surfaces. Calif. Dep. Transp. 2011.

Yen, K.S.; Ravani, B.; Lasky, T.A. LiDAR for Data Efficiency; AHMCT Research Center: Davis, CA, USA, 2011.

Young, A.P.; Olsen, M.J.; Driscoll, N.; Flick, R.E. Comparison of airborne and terrestrial lidar estimates of seacliff erosion in. Photogramm. Eng. Remote Sens. 2010, 76, 421–427.

Zampa, F.; Conforti, D. Mapping with mobile lidar. GIM Int. 2009, 23, 35–37.