IDEA

Innovations Deserving Exploratory Analysis Programs

Highway IDEA Program

Three-Dimensional Digital Imaging for the Identification, Evaluation and Management of Unstable Highway Slopes

Final Report for Highway IDEA Project 119

Prepared by:
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March 2008

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)

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Three-Dimensional Digital Imaging for the Identification, Evaluation and Management of Unstable Highway Slopes

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1.0 Executive Summary

New technologies are becoming increasing important for the design, construction and maintenance of highways. Rockfall along highways is a major safety hazard and can result in extensive damage to the highway infrastructure. Because of the safety and financial issues posed by rockfall along highways, new technologies are needed for the identification, evaluation and management of unstable slopes prone to rockfall.

The “idea” in this research is to utilize ground-based LIDAR, in conjunction with point cloud processing algorithms, to assist with the identification, evaluation and management of highway slopes that are prone to rockfall. This includes the assessment of rock faces for the likelihood of rockfall (rockfall hazard ratings and rock mass characterization), as well as determining information on rockfall that actually occurs (locations, rate and volume of rockfall). Software development is made through improvements to Split Engineering’s Split-FX software for processing point clouds and associated digital images. In addition, seven field sites in Arizona, Colorado and Utah have been utilized to field-test the software and develop best practices.

The project is divided into two stages. In Stage 1 several sites were identified for field testing of the software. Some scans were conducted in rockfall prone locations and rescanned again in Stage 2. One of the locations for repeated scanning is Interstate 70 near Georgetown, CO. This is a location where a number of fatalities due to rockfall have occurred in recent years. Another site for repeated scans is Big Cottonwood Canyon, Utah. Software development in Stage 1 consisted of adding the following features to the Split-FX program: improved import and export options, new 3D visualization tools, new stereonet contouring tools, tools for measuring joint spacing and block volume, and a tool for generating slope profiles from 3D point clouds. These tools can be used for rock mass characterization, rockfall runout studies, and to measure many of the parameters associated with Rockfall Hazard Rating systems.

In Stage 2, repeated LIDAR scans were conducted at the Utah and Colorado sites mentioned above. Software has been developed in Stage 2 to first of all align scans taken at different times using an Iterative Closest Point (ICP) algorithm. Then the change between the two scans is determined, giving the location and volume of rockall events as well as the total accumulated rockfall volume during the time period between scans. Experiments conducted at a field site in Arizona determined that the change detection algorithm could detect the movement of boulders as small as 15 cm. Software has also been developed in Stage 2 to “drape” a high-resolution digital image onto a point cloud. This allows two-dimensional traces on the digital image to be converted into three-dimensional planes.

This project has the potential of increasing safety and reducing the occurrence of rockfall on highways by improving the prediction of unstable rockfall areas and by being able to accurately assess the source locations and volumes of rockfall that does occur.

The end products of this research include the development of engineering techniques for rockfall prediction and assessment, as well as point cloud software. The software consists of additional capabilities added to the existing Split-FX software, which currently has a database of users and is marketed to interested parties through its web site, meetings, and a number of other ways.

2.0 IDEA Concept and Product

2.1 Background

Rockfall along highways is a major safety hazard and can result in extensive damage to the highway infrastructure (Badger and Lowell, 1992; Schuster and Fleming. 1986; Bunce et al., 1997). Rockfall prevention using rockfall fences and other devices is now routinely used, however these devices are expensive and require ongoing maintenance. Rockfall Hazard Ratings are also used to determine slopes that are likely to produce rockfall, but the techniques used to determine the ratings are antiquated and pose safety risks to highway personnel. Figure 1 shows examples of rockfall along Interstate 70 in Colorado. Because of the safety and financial issues posed by rockfall along highways, new technologies are needed to address the following issues:

- Accurate identification of the source of rockfall events
- Accurate determination of rockfall volume and rates
- Accurate determination of Rockfall Hazard Ratings
- Ability to capture data safely from a distance
- Ability to capture and process data quickly

Figure 1. Examples of rockfall. Interstate 70 after 2004 Glenwood Canyon rockfall (left); Rockfall filling a rockfall capture device along Interstate 70 near Georgetown, CO (right).

2.2 New Technologies: Ground-based LIDAR and point cloud processing software

New technologies are becoming increasing important for the design, construction and maintenance of highways. Ground-based LIDAR (also called 3D laser scanners) along with high-resolution digital imaging is a potential new technology to address the issues described above. Figure 2 shows an example of a LIDAR scan being conducted along a highway slope in Arizona. LIDAR scanning is conducted at a distance from the slope, eliminating potential safety hazards. Also, surveying points used to register the scan can be conducted at points in front of the rock face, eliminating the safety hazard of using surveyed targets on the slope (see Figure 2). The output from a laser scanner survey is a “point cloud” consisting of millions of reflection points that represent the 3D surface that was scanned. Figure 2 shows the point cloud created

from the scan of the rock slope. After some data cleaning, a triangulated surface can be rendered from the point cloud data, and many subsequent calculations and visualizations can be made using the 3D surface. In addition, a technique called texture mapping or photo draping can be used to overlay high-resolution color information from digital images onto the 3D surface. Additional information on the accuracy and features of ground-based LIDAR units can be found at POB (2007).

Figure 2. Example of ground-based LIDAR scanning, Milepost 15 on Mt. Lemmon Highway, AZ. Scanning conducted with the Leica ScanStation (Leica, 2008). Point cloud is registered using surveyed nails in the highway. Point cloud consists of about 1.5 million points.

Split Engineering LLC has recently developed a software package, Split-FX, for processing LIDAR point clouds to extract geotechnical information (Split Engineering, 2008). This software is able to automatically delineate fractures in point clouds, plot stereonets of fracture orientations, perform automatic or manual tracing on digital images for joint length and spacing, and other features. This information can provide much of the information needed for rock mass characterization in a semi-automated fashion that is quick, results in orders of magnitude more data, and avoids human bias issues. Figure 3 illustrates the basic steps in Split-FX to extract information on fracture orientation from LIDAR point clouds. Additional information on semi-automated rock mass characterization using LIDAR point clouds can be found in Kemeny et al. (2006a, b and c).

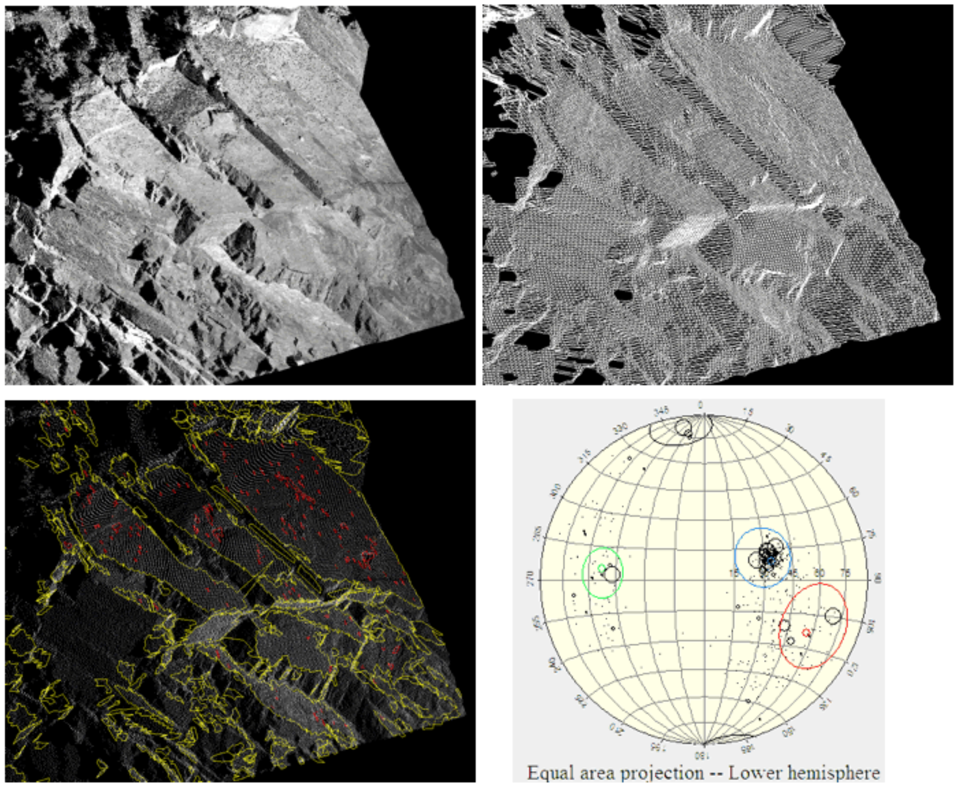


Figure 3: Basic steps using Split-FX for rock mass characterization: a) point cloud, b) triangulated mesh, c) automatic fracture delineation, d) stereonet plotting of fracture poles.

2.3 The IDEA

The "idea" in this research is to utilize ground-based LIDAR, in conjunction with point cloud processing algorithms, to assist with the identification, evaluation and management of highway slopes that are prone to rockfall. This includes the assessment of rock faces for the likelihood of rockfall (rockfall hazard ratings and rock mass characterization), as well as determining information on rockfall that actually occurs (locations, rate of rockfall, volume of rockfall). Software development is made through improvements to Split Engineering's Split-FX software for processing point clouds and associated digital images.

The idea consists of three types of analyses utilizing LIDAR scans and point cloud processing software:

1. Repeated LIDAR scans are conducted of the same rock face at subsequent times. A change detection algorithm (such as the Iterative Closest Point (ICP) algorithm) is then used to accurately align the two point clouds and subtract them, producing a difference point cloud. This can then be used to either graphically visualize areas where rockfall has occurred or make calculations to determine rockfall rates and volumes.
2. LIDAR point clouds along with high resolution digital images are used to accurately determine the Rockfall Hazard Rating. This involves developing specific software tools

to determine the various parameters in rockfall rating systems, including the measurement slope height, ditch effectiveness, road width, block size, etc.

3. Detailed rock mass characterization can be carried out at the source locations of rockfall events using LIDAR point clouds to evaluate rock mass stability and to determine the specific cause of the rock fall events.

In addition to software development, field case studies in Arizona, Colorado and Utah have been conducted to field test the three types of analyses described above.

2.4 Innovation

The development of LIDAR and point cloud processing technologies for rockfall assessment addresses all of the issues described in Section 2.1. These technologies will allow rockfall events to be identified, including the determination of rockfall volumes and rates. Through the semi-automated determination of Rockfall Hazard Ratings, these technologies can be used to identify and mitigate unstable slopes. Through automated rock mass characterization and rapid export to slope stability programs, these technologies can also be used to determine the underlying cause for the rockfall events, which allows remediation measures to be designed and employed. These technologies allow rockfall assessment to be conducted from a distance from unstable slopes, thereby increasing safety. Finally, these technologies allow for rapid data collection and analysis of results, and minimizes human bias issues. Overall there are many safety and financial benefits to employing the new technologies.

3.0 Investigation

The investigation consists of two major tasks, software development and field testing, as described in Sections 3.1 and 3.2, respectively. In addition, specific examples showing the usefulness of the newly developed techniques and software for rockfall hazard ratings and change detection are discussed in Sections 4.1 and 4.2, respectively.

3.1 Software Development

Specific point cloud processing algorithms were developed for conducting the three types of rockfall analyses described in Section 2.3. These algorithms are described below

1. Change Detection Algorithm. This algorithm evaluates two point clouds taken of the same terrain, but at different times. First, an Iterative Closest Point (ICP) algorithm aligns the two point clouds. Secondly, the two clouds are subtracted, resulting in a “difference cloud”. Any rockfall events that have occurred between the times of the two scans should be detected by the difference scan (missing blocks on the slope, displaced blocks, accumulation of rock at the base of the slope, etc.). Rockfall volumes and rockfall rates can also be calculated from the difference cloud. The difference cloud can be visualized in a variety of ways to highlight different aspects of the rockfall, as illustrated in Figure 4.

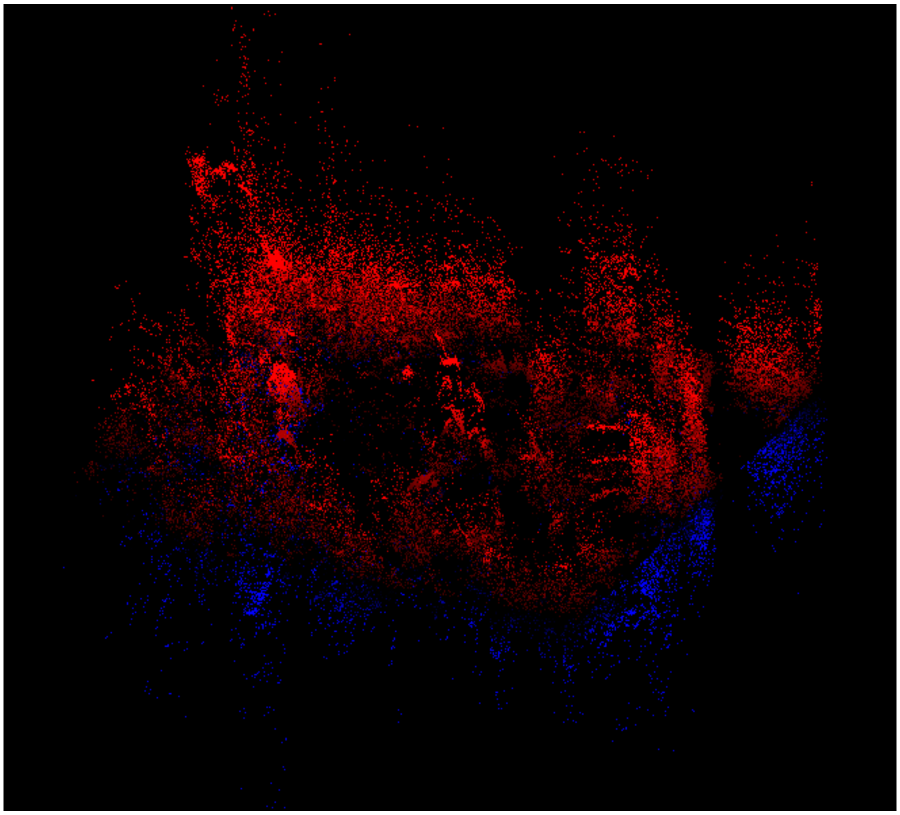


Figure 4. Difference point cloud, colored to visualize positive (blue) vs. negative (red) change, and to eliminate small amounts of change below the ICP noise level (black).

2. <u>Tools for Determining Rockfall Hazard Ratings.</u> Many states have adopted a rockfall hazard rating system that first gives A, B or C ratings to slopes (A being the worst). A detailed evaluation is then made on the A-rated slopes based on a number of rock and highway factors. Some commonly used factors are shown in Figure 5.

1. Slope height
2. Ditch effectiveness
3. Average vehicular risk
4. Sight distance
5. Roadway width
6. Structural condition (discontinuities)
7. Rock friction
8. Structural condition of eroded rock
9. Difference in erosion rates
10. Block size or volume of rockfall per event
11. Climate and presence of water on slope
12. Rockfall history.

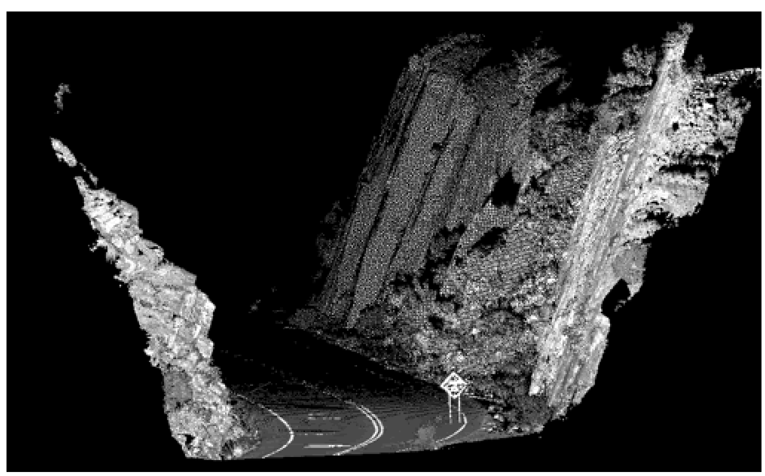


Figure 5. Typical factors used in determining a Rockfall Hazard Rating (left), many of which can be extracted from LIDAR point clouds (right) using tools that have been developed.

Many of these parameters can be extracted from LIDAR point clouds (such as the one shown in Figure 5), and the following tools have been developed to assist with this process:

- Distance measuring tool for point clouds and digital images
- Area measuring tool for digital images
- Volume measuring tool for point clouds

Examples of these tools are shown in Figure 6. These tools can also be used to measure rockfall parameters from the difference point clouds.

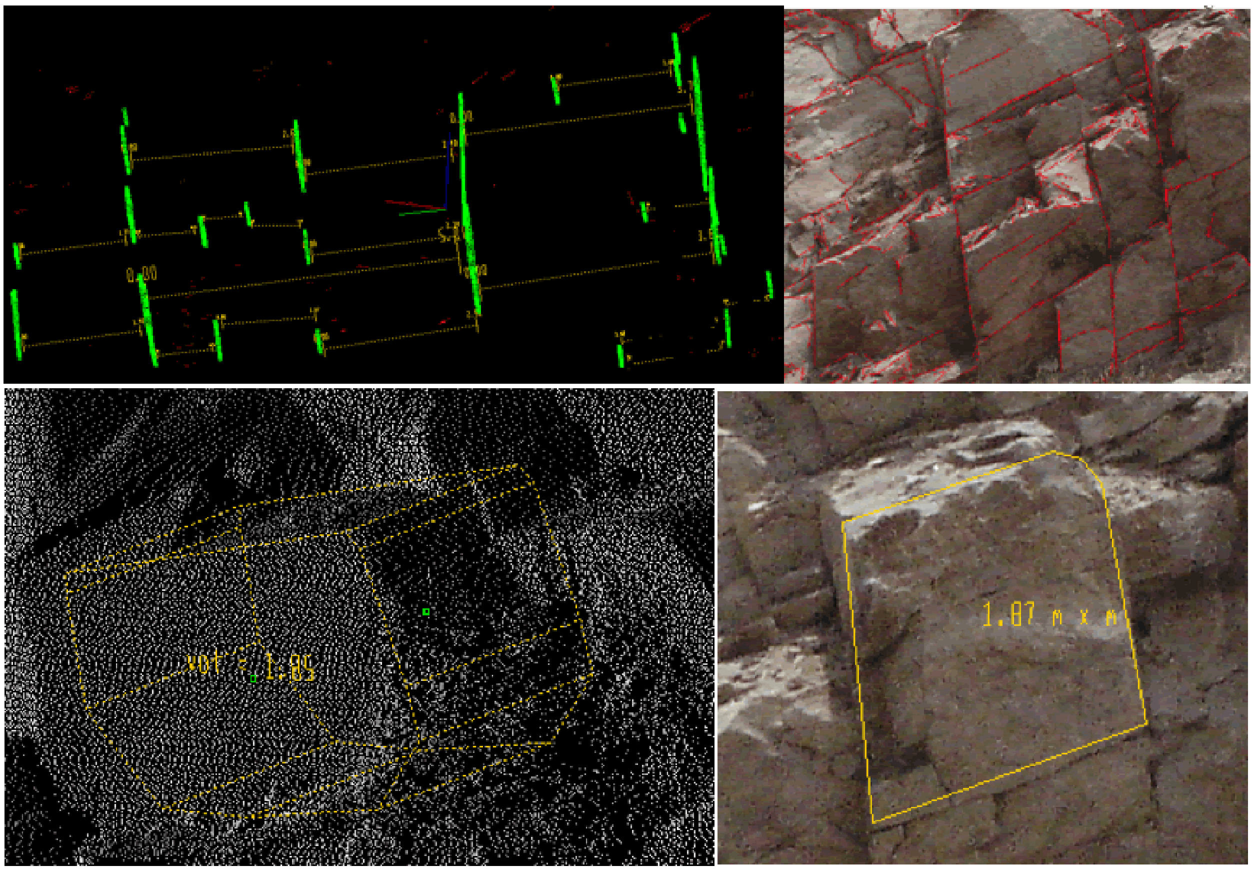


Figure 6. Examples of the distance measuring tool (top figures) and the area and volume measuring tools (bottom figures) on point clouds (left figures) and digital images (right figures).

3. <u>Cross sections through point clouds/triangulated meshes.</u> Tools were added for making cross sections through the 3D model that consists of the point cloud, triangulated mesh and fracture patches. Cross sections are important for several aspects of rockfall assessment. First of all, the cross section tool can be used to create a slope profile and to determine rockfall runout behavior, as illustrated in Figure 7. Also, the cross section tool can be used to correlate three-dimensional fractures in the point cloud with two-dimensional traces in digital images. Finally, the cross section tool can be used to make single discontinuity profiles in the direction of block sliding to determine the roughness and friction angle characteristics of the fractures, as shown in Figure 8.

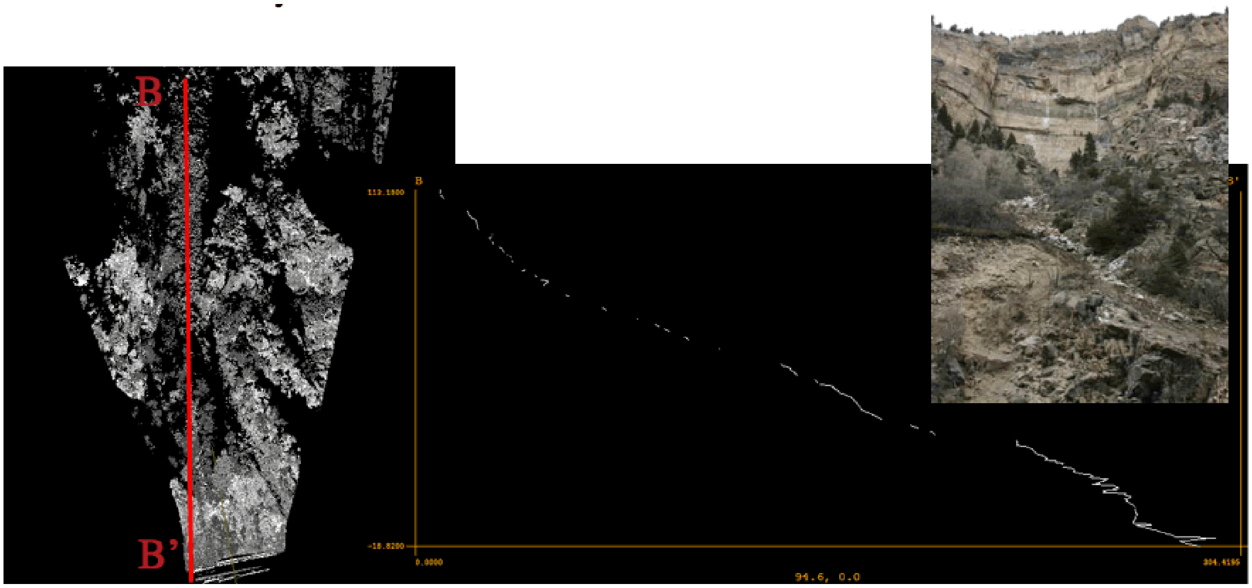


Figure 7. Cross section through the runout chute for the 2004 Glenwood Canyon rockfall, determined using the triangulated mesh from the LIDAR scan and the cross section tool.

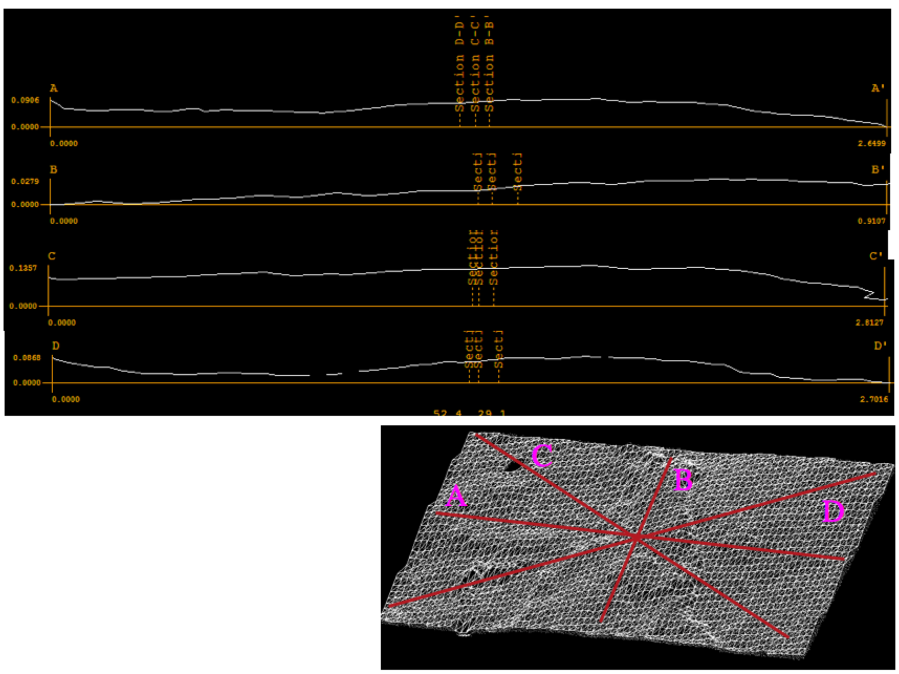


Figure 8. Cross sections through a single rock discontinuity in different directions, which can be used to estimate discontinuity roughness and discontinuity friction angle.

4. <u>Rapid Export to Slope Stability Programs.</u> In order to rapidly assess the potential for slope instability and rockfall associated from LIDAR scans of highway slopes, new import and export options were added to Split-FX. Split-FX can now import point clouds with a wide range of formats (including color LIDAR scans), and has the ability to export to other programs, including slope stability software.

5. <u>Photo Draping.</u> The ability to drape a high-resolution 2D digital image over a triangulated mesh from a point cloud was added. The photo draping feature is important for rockfall assessment for several reasons. First of all, adding the high-resolution digital image to the point cloud facilitates the interpretation of geology, structure and potential rockfall locations. Secondly, tracing on the draped photo produces three-dimensional information of the traced object (3D fracture orientation from the trace of a fracture, for instance). Also, the color Digital Terrain Model (DTM) produced from the photo draping will be able to be exported in a standard format to other programs.

6. <u>Added Fracture Visualization and Contoured Stereonets.</u> One of the important steps in rockfall assessment using LIDAR is the ability to clearly see the rock discontinuities, including joints, faults, and bedding planes. New features were added to be able to more clearly visualize these discontinuities in three dimensions. Also, the ability to make two types of stereonet contour plots has been added (Kamb contour and 1% area contour plots). These features are shown in Figure 9.

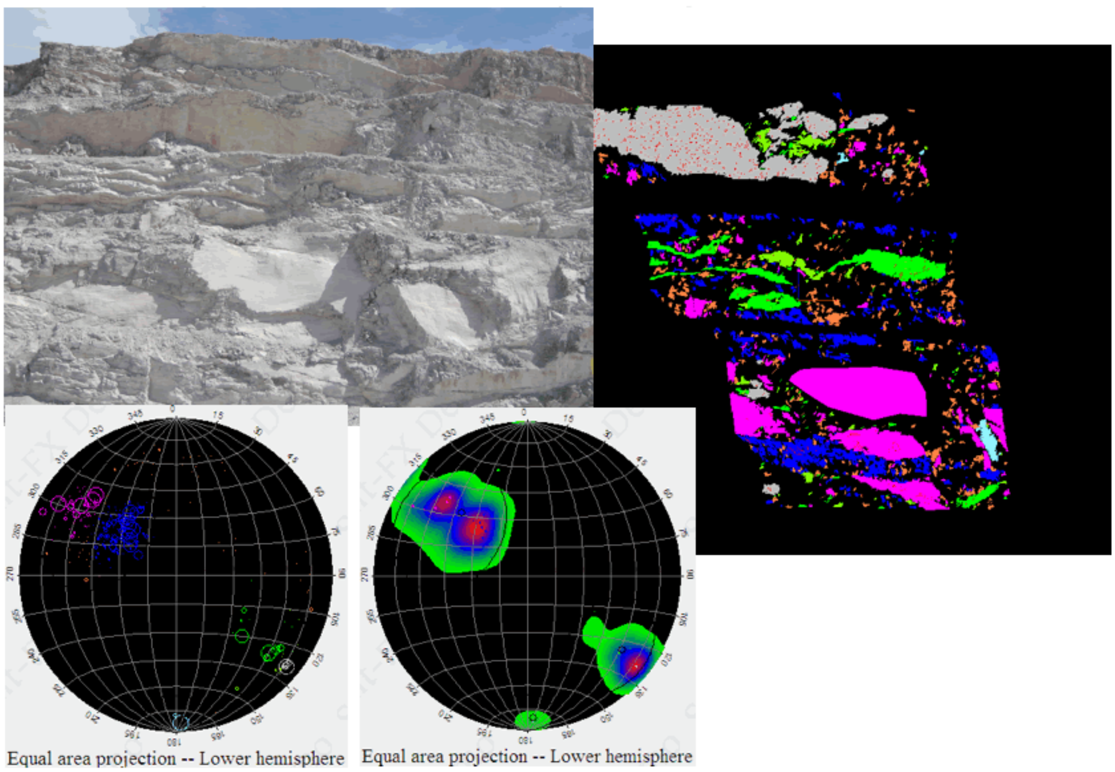


Figure 9. New fracture visualization features were added to both the point cloud (right figure) and the stereonet plotting of fracture poles (contoured stereonet).

<u>3.2 Field Testing</u>

Field testing was conducted at 7 field sites in Arizona, Colorado, and Utah. Details on these field sites are described below.

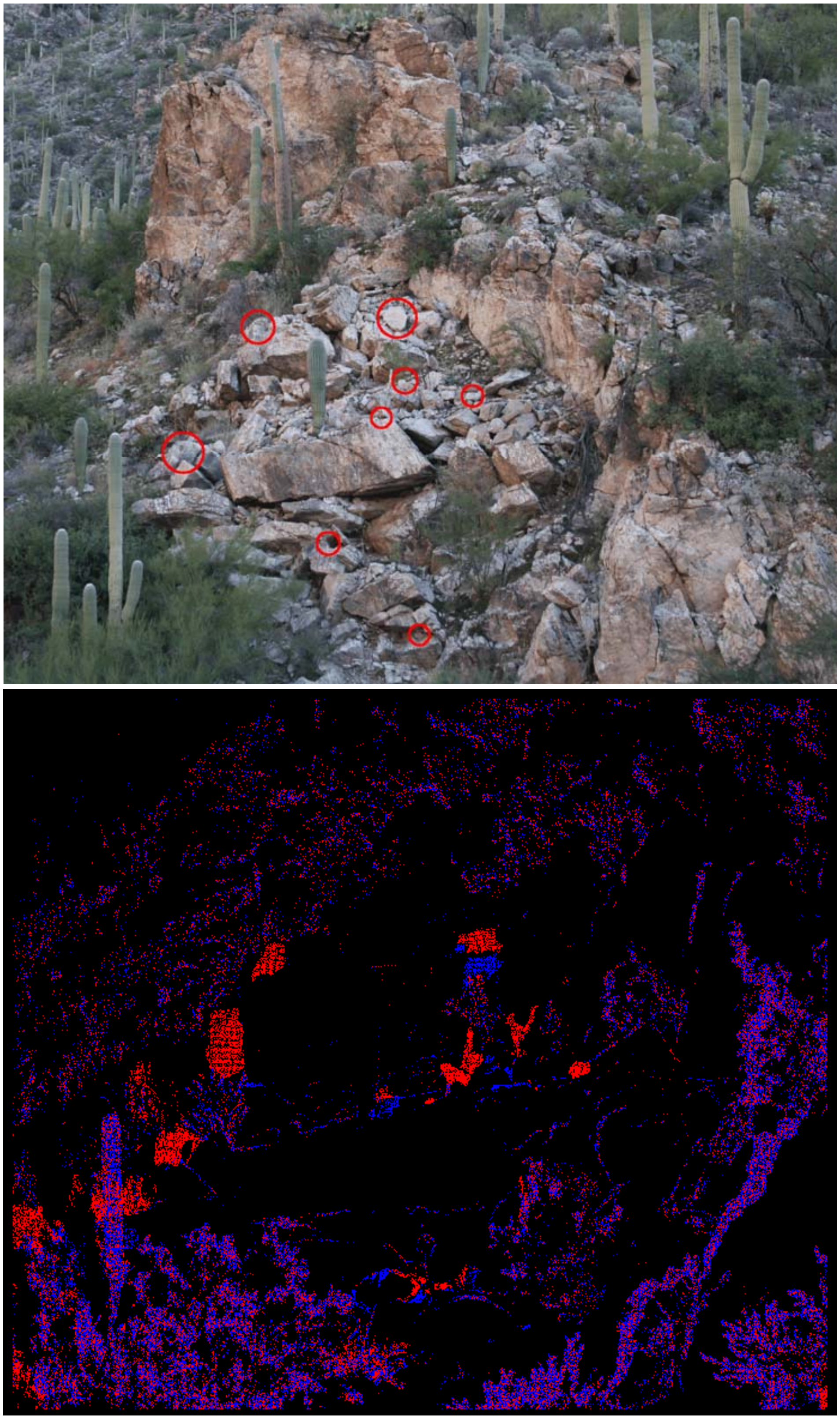
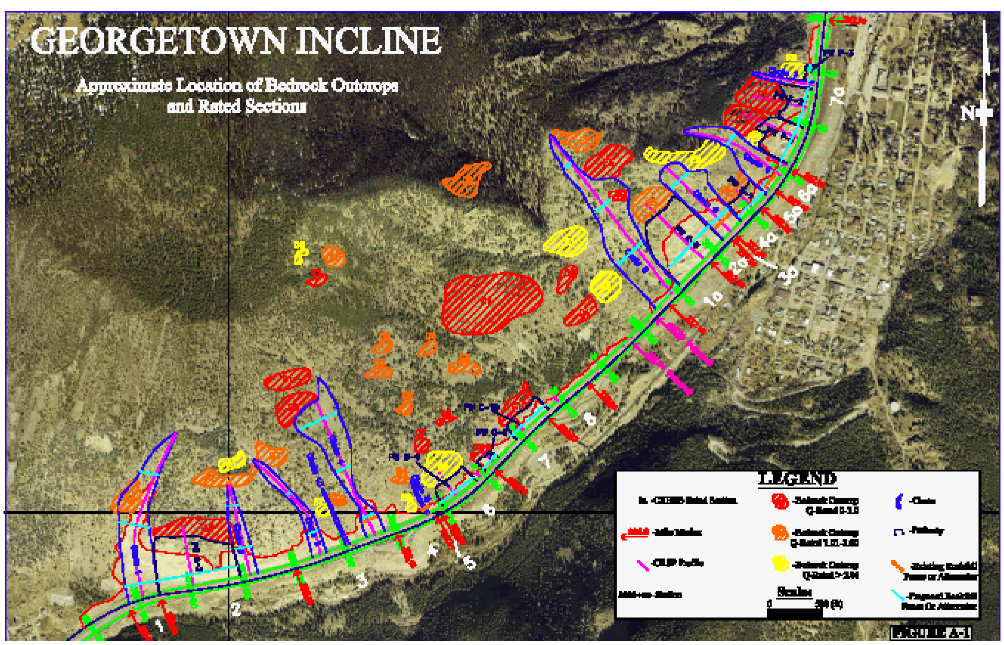


Figure 10. Field site for testing the change detection algorithm. Boulders marked with red circles were moved (top image). From the difference point cloud (bottom image), the movement of boulders as small as 15 cm were detected. Red indicates missing material, blue indicates new.

1. <u>Milepost 2, Mt. Lemmon Highway, Arizona.</u>
This site was used to test the change detection algorithm that was developed. A “rolling rock” experiment was conducted where 8 boulders with sizes from 10 to 100 cm were moved, as shown by the red circles in Figure 10a. Before and after scans were taken. The Iterative Closest Point (ICP) algorithm was applied and a difference point cloud was produced, as shown in Figure 10b. From this field site it was determined that the movement of boulders as small as 15 cm can be detected.

2. <u>Milepost 15, Mt. Lemmon Highway, Arizona</u>
This site was used to test photo draping, rock mass characterization tools, and the change detection algorithm, and also to develop best practices for field LIDAR scanning. Some pictures of this site are shown in Figure 1. Scans at this site were conducted with three scanners, the Optech Ilris3D, the Leica HDS 3000, and the Riegl Z360. In addition to scanning, 110 manual fracture orientation measurements were made to compare with LIDAR results. 30 survey control points were installed on the highway (survey nails, see Figure 2) in order to test scanner registration accuracy.

3. <u>Interstate 70 Near Georgetown, Colorado</u>
This site is a location where a significant amount of rockfall occurs, and where a number of fatalities due to rockfall have occurred in recent years. Figure 11 shows a map of rockfall source areas and rockfall chutes in the Georgetown area of Interstate 70 (from CDOT, 2005). The rockfall source areas are located as far as 1000 meters from the highway, making traditional rock mass characterization very difficult. Permanent markers were installed by CDOT personnel in 2006 at about 20 locations. A map showing some of these locations is presented in Figure 11. In 2006, scans at these locations were made (Figure 11). Rescanning was then conducted in 2007 to investigate rockfall occurrences. A discussion of the change detection results from this site is given in Section 4.2.



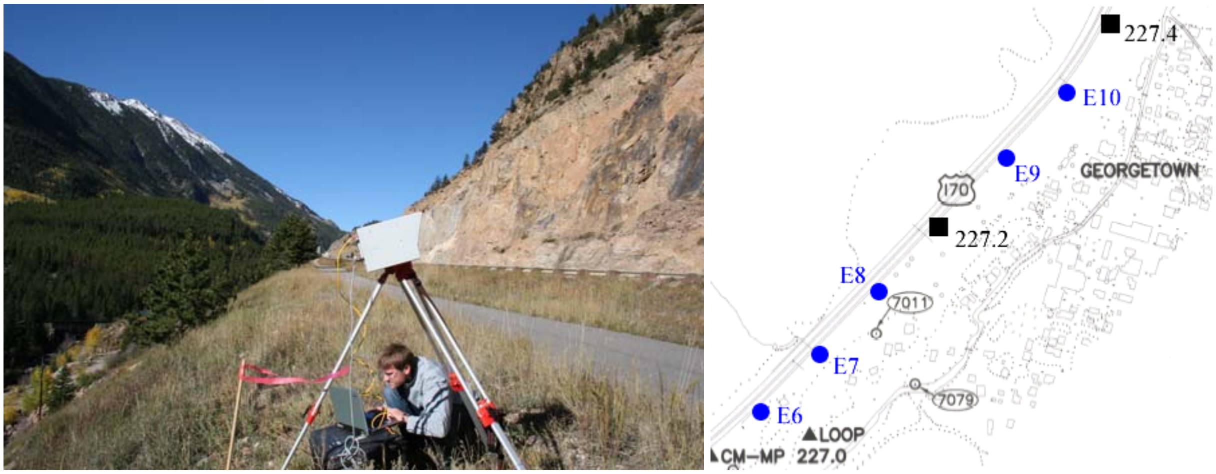


Figure 11. Top figure: Map showing rockfall source areas (striped areas) and rockfall chutes (blue) on the north side of Interstate 70 near Georgetown, CO (from CDOT, 2005). Bottom figures: LIDAR scanning, and locations of some of the permanent benchmarks.

4. State 74 near Morrison, Colorado

LIDAR scans were made at the Bureau of Reclamation 3D visualization test site near Morrison, Colorado. This site has previously been used as a test site for various photogrammetry methods for rock mass characterization. Scans were conducted at this site with both the Optech Ilris3D and Trimble GS200 scanners. This site is used to compare LIDAR results with photogrammetry (Figure 12), to compare different methods of scanner registration, to test rock mass characterization tools, and to develop best-practices for field scanning.

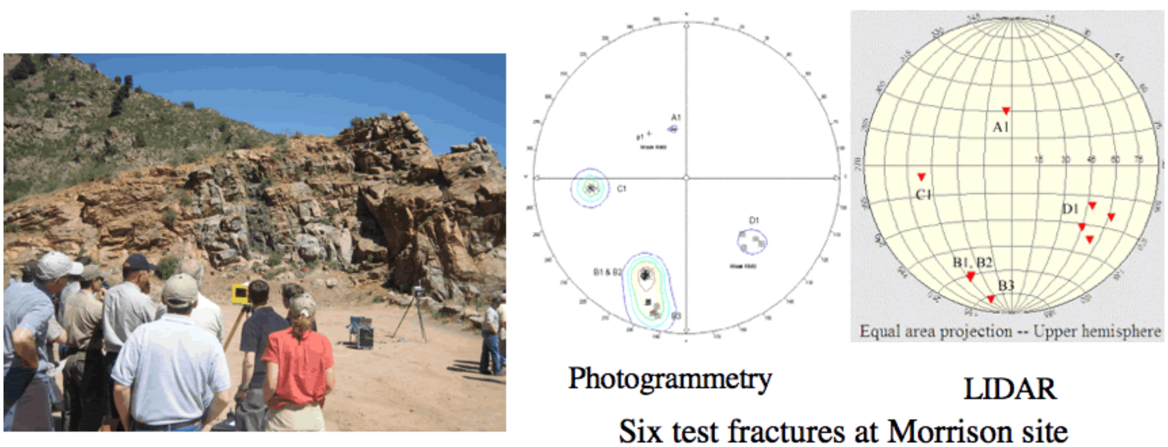


Figure 12. Morrison field site. Comparison of photogrammetry with LIDAR for six test fractures.

5. State Route 190, Big Cottonwood Canyon, Utah

In 2006 Scans were performed along State Route 190 (SR 190) in Big Cottonwood Canyon, Utah. SR 190 runs eastward from the mouth of Big Cottonwood Canyon at Wasatch Boulevard to the Brighton ski area. The road is approximately 16 miles long and contains along its length 39 inventoried and rated rockfall sites. Of these 39 sites, 8 have been designated with rockfall

hazard ratings of *A* indicating immediate potential for rockfall danger. Examples of the scanned sites are shown in Figure 13.

Figure 13: Examples of scanned sites along SR 190.

This site is being used to test the point cloud processing tools for determining the Rockfall Hazard Rating. Also, additional scans were made in 2007 to investigate rockfall occurrences.

6. Interstate 70 through Glenwood Canyon, Colorado
Scans were made at the location of the “Thankgiving Rockfall” that occurred on Thanksgiving Day in 2004 (CDOT, 2007). Pictures of this site are shown in Figure 6. From the scans some details of the rockfall event were determined using the new measurement tools (such as the rockfall volume). Also, using the cross section tool, details of the rockfall runout path were determined (Figure 7).

7. Mt. Seymour Road, Vancouver, BC
As part of a LIDAR/photogrammetry workshop, a highway field site was selected and LIDAR scans were made with Leica, Isite, and Optech scanners. In addition to the scans, digital images for analysis using photogrammetry software were also taken, and ground-truth data was collected using traditional methods (scanline surveys). The LIDAR scans at this site were used as part of rock slope stability/rockfall software validation and accuracy.

8. Highway 60 near Globe, Arizona.
Several scans were taken in this area to determine if rockfall hazard ratings can be determined using LIDAR scans, and this is described in more detail in Section 4.1 below.

4.0 Rockfall Hazard Rating and Change Detection Examples

In this section, some examples of using LIDAR to assist with the evaluation of highway slopes are described. In particular, these examples demonstrate how the new techniques and software developed in this research are used to assess the risk of rockfall. In the first example, LIDAR scans of a 57 meter length of Highway 60 near Globe, Arizona are analyzed to determine a rockfall hazard rating. In the second example, repeated scans at several locations are analyzed to locate rockfall events that have occurred.

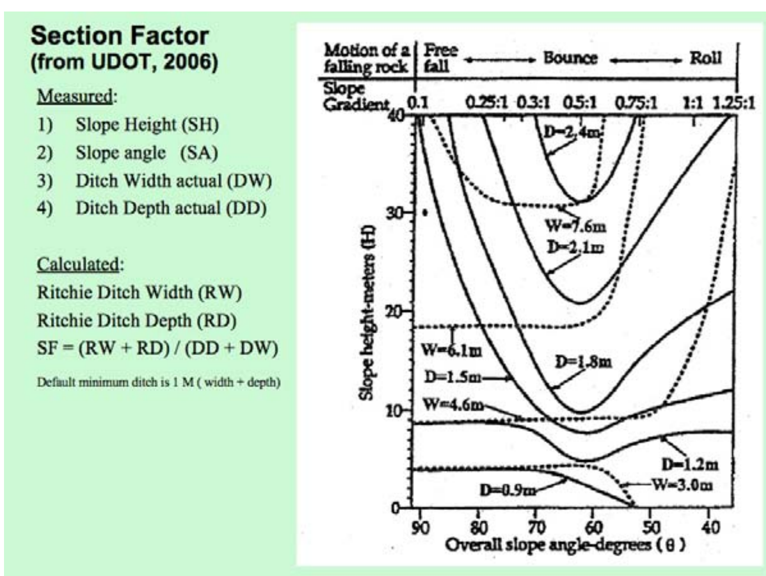
4.1 Rockfall Hazard Rating Example

The Utah Department of Transportation (UDOT) recently developed a Rockfall Hazard Rating System (RHRS), described in Pack et al. (2006). The system is modeled after both the Oregon (Pierson et al., 1990)) and New York (Hadjin, 2002) systems. The system has three factors, the Geologic Factor (GF), the Section Factor (SF) and the Human Exposure Factor (HEF). From these three factors the Total Relative Risk (TRR) is calculated, which ranges from less than one to over 1000 (higher numbers more critical). The Geologic Factor has 6 parameters (Figure 14a), the Section Factor has 4 parameters (Figure 14b) and the Human Exposure Factor has 5 parameters (Figure 14c). The equations for the calculation of the TRR are also shown in Figure 14c. Of the 15 parameters in the UDOT RHRS system, 12 of the parameters can be determined from LIDAR point clouds and associated digital images, as described below.

Geologic Factor (GF) from UDOT (2006)

		1	3	9	27	81
1A	Crystalline Geology	Massive, no fractures dipping out of slope	Discontinuous fractures, random orientation	Fractures that form wedges	Discontinuous fractures dipping out of slope	Continuous fractures dipping out of slope
1B	Layered Geology	Horizontal to slightly dipping	Raveling, occasional small blocks	Small overhangs or columns, numerous small blocks	Overhangs, some large unstable blocks, high columns	Bedding or joints dipping out of slope, over-steepened cut face
2	Block Size	150 mm	150 to 300 mm	0.3 to 0.6 m	0.6 to 1.5 m	1.5 m or more
3	Rock Friction	Rough, Irregular	Undulating	Planar	Smooth, slickensided	Clay, gouge-faulted
4	Water/Ice	Dry	Some seepage	Moderate seepage	High seepage/brush	High seepage with long backslope/brush
5	Rock Fall	No falls	Occasional minor falls	Occasional falls	Regular falls	Major falls/slides
6	Backslope Above Cut	Flat to gentle slope (up to 15 deg)	Moderate slope (15 to 25 deg)	Steep slope (25 to 35 deg)	Very steep slope (>35 deg) or steep slope (25 to 35 deg with boulders)	Very steep slope (>35 deg) with boulders

a)



b)

Example Data Sheet for RHRS determination from LIDAR, based on
UDOT Rockfall Hazard Rating System: Final Report and Userís Manualî, Report No. UT-06.07

Site location: Hwy 60 near Globe, Arizona (scans h602 and h603)

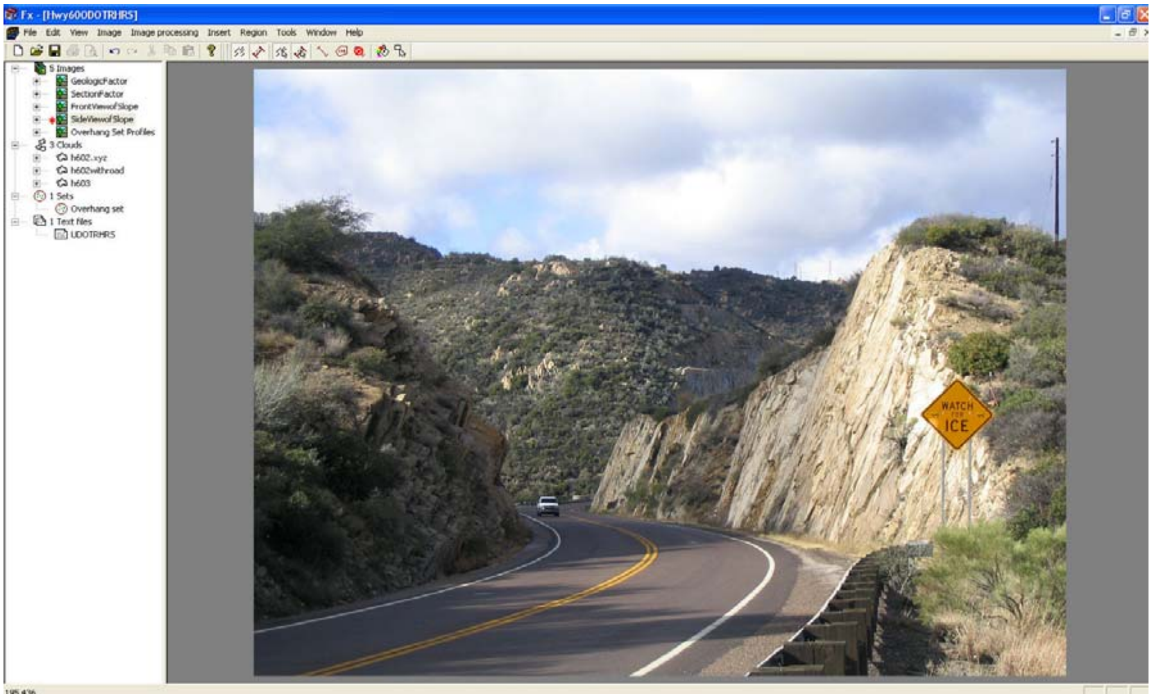
Parameter	Rating	Comments
GEOLOGIC FACTOR (GF)		
1a Crystalline geology	27	Major overhanging discontinuities with strike of 254, parallel to road cut (strike 252)
1b Layered geology	NA	
2 Block size	9	Based on an average block size of approximately 0.4 meters
3 Rock friction	3	Based on discontinuity profiles of overhang set
4 Water/ice	1	From digital image no water visible
5 Rockfall history	27	No actual data, but rockfalls likely occur regularly based on site conditions
6 Backslope	1	
Total GF	10.4	GF = (Geology + 2*Block_Size + Rock_Friction + Water + 2*History + Backslope)/10
SECTION FACTOR (SF)		
1 Slope height (m)	20	
2 Slope angle	58	
3 Ditch width (DW)	0	
4 Ditch depth (DD)	0	
Ritchie Ditch width (RW)	6.3	Determined from Ritchie chart
Ritchie Ditch depth (RD)	2.1	Determined from Ritchie chart
Total SF	8.4	SF = (RW + RD)/(DD + DW)
HUMAN EXPOSURE FACTOR		
1. Average daily trafic (ADT)	1500	Estimate only
2 Horizontal distance of site, m (L)	57	
3 Velocity (km/hr) (V)	88	
4 AASHTO stopping distance, m (SSD)	168	From AASHTO table (desirable column using wet friction)
5 Actual stopping distance, m (DSD)	> 168	Site distance from East only, no scan on west side of site
Total HEF	6.8	HEF = (Fa + Fp)/3 Fa = (ADT) x ((L + SSD)/ (V x 24,000)) Fp = log10 (ADT) x (Log10 (L) x(A/(SSD - A))) A = max[(SSD - DSD),0]
TOTAL RELATIVE RISK (TRR)	594	TRR = GF x SF x HEF

c)

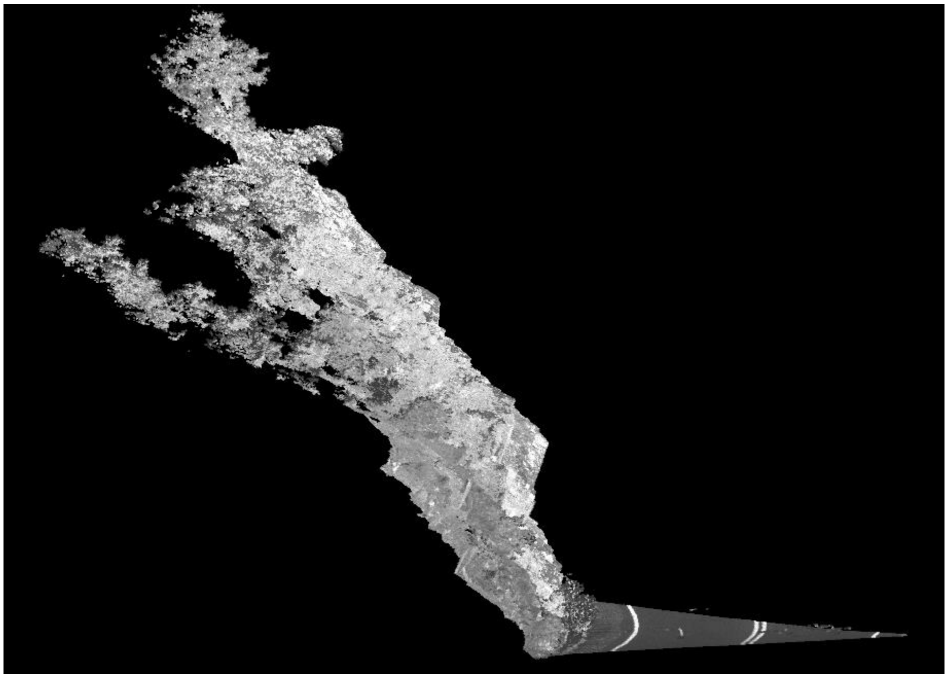
Figure 14. Details of the UDOT RHRS system. a) Geologic Factor, b) Section Factor, c) data sheet for calculating the Total Relative Risk for the slope along Highway 60.

The site chosen is a section of Highway 60 near Globe, Arizona. Figure 15a shows the overall site, and Figure 15b shows the specific slope where the rockfall hazard rating was calculated (you can also see this slope in Figure 15a). The geology consists of crystalline geology with overhanging discontinuities that strike parallel to the highway. LIDAR scans were taken of the specific slope as well as a scan showing both sides of the highway, as shown in Figures 15c and 15d.

Determination of the individual parameters in the Geologic Factor (GF) were made as follows: An analysis of the discontinuity orientations is made using Split FX, as shown in Figure 16a. The overhanging set is shown in green and from its orientation it can be verified that the overhanging set strikes parallel to the highway, giving a crystalline geology rating of 27 (see Figure 14a and 14c). Block size was determined using the FX feature shown in Figure 6, giving a rating of 9. The friction parameter for the overhanging discontinuities was determined by making profiles, as described in Section 3.1 and shown in Figure 8. The profiles for the overhanging joint set are shown in Figure 16b, giving a friction rating of 3. No evidence of water was visible from the digital images, giving a water/ice rating of 1. Since no repeated scans were taken of the site, the rockfall history rating could not be determined from the LIDAR scans. A rating of 27 was given based on the structural analysis in Figure 16a. A backslope rating of 1 was given based in the slope geometry determined from the LIDAR point cloud shown in Figure 15c. Finally, using the equation in Figure 14c gives a Geologic Factor of 10.4.

a) 
Fx - [Hwy600DOTRHRS]
File Edit View Image Image processing Insert Region Tools Window Help
5 Images
GeologicFactor
SectionFactor
FrontViewofSlope
SideViewofSlope
Overhang Set Profiles
3 Clouds
h602.xyz
h602withroad
h603
1 Sets
Overhang set
1 Text files
UDOTRHRS
WATCH FOR ICE

b) 

c) 

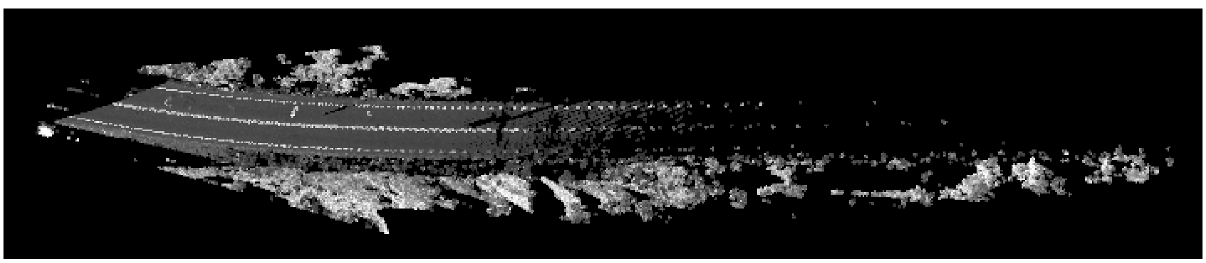
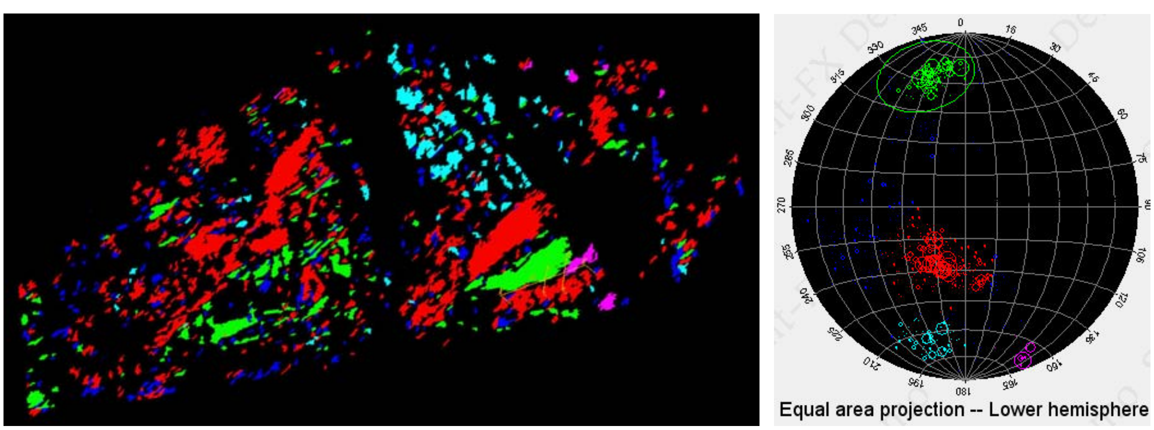
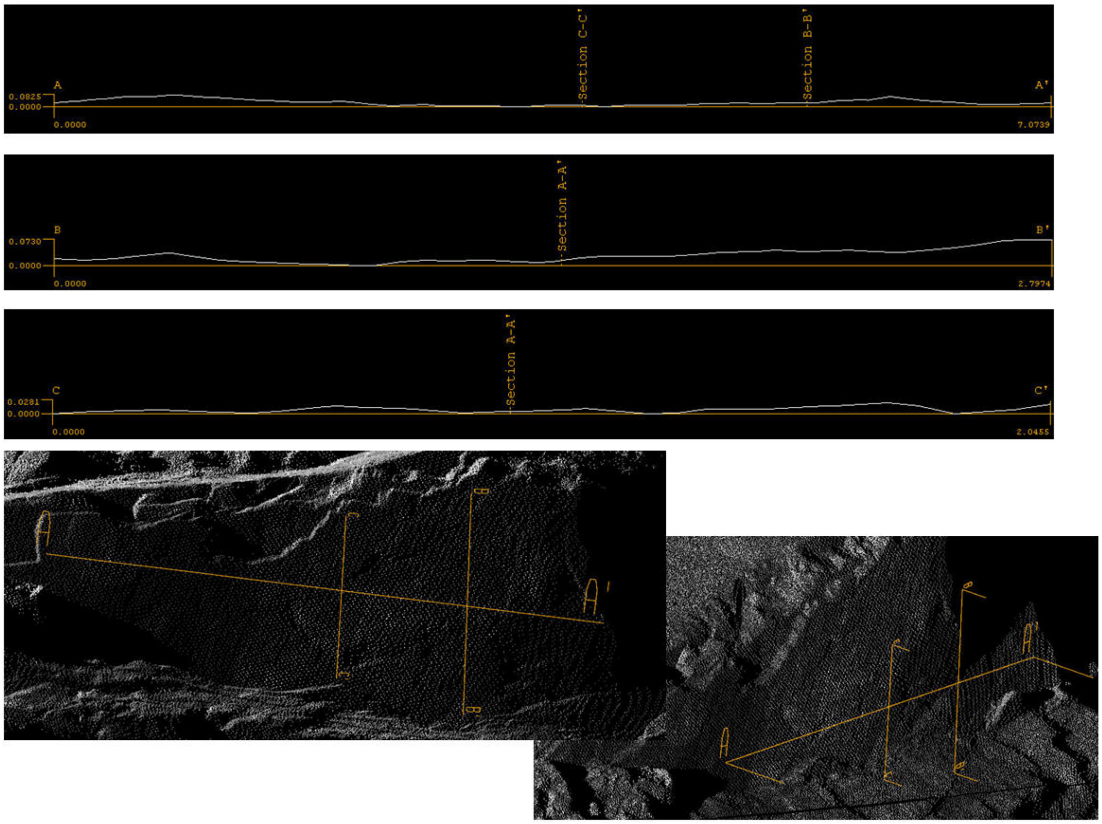
d) 

Figure 15. Digital images and point clouds used to determine the UDOT RHRS for a 57 meter cut along Highway 60 in Arizona, a) digital image parallel to highway with road cut on left, b) digital image of cut, c) point cloud h602 to determine discontinuity characteristics, slope height and angle, ditch parameters, d) top down view of point cloud h603 with cut on upper left to determine width of highway and stopping distance (the front view of this point cloud is shown in Figure 5).

a) 



b)

Figure 16. a) delineated fractures in the section of Highway 60 being evaluated showing the overhanging set (green) striking parallel to highway, b) roughness profiles made on the overhanging set (A-A', B-B', C-C') to determine the friction parameter.

Determination of the individual parameters in the Section Factor (SF) were made as follows: the Section Factor parameters involve determining slope height, slope angle, ditch width and ditch depth from the point clouds, which is straightforward using the point cloud in Figure 15c, giving values of 20 meters, 58 degrees, 0 meters and 0 meters, respectively. From these measurements the Richie Ditch Width and Depth are determined using the chart in Figure 14b, giving values of 6.3 and 2.1 m, respectively. Finally, using the equation in Figure 14c gives a Section Factor of 8.4.

Determination of the individual parameters in the Human Exposure Factor (HEF) were made as follows: Two of the parameters, the horizontal distance of site and the actual stopping distance, were determined using the point cloud given in Figure 15d, giving 57 m and >168 m, respectively. Three of the parameters, the average daily traffic, the average velocity, and the AASHTO stopping distance, could not be determined from LIDAR scans. However, these parameters are easily determined from known traffic statistics, the posted speed limit, and AASHTO tables, giving 1500, 88 km/hr. and 168 m, respectively. Finally, using the equation in Figure 14c gives a Human Exposure Factor of 6.8 and a final Total Relative Risk of 594.

In summary, this example demonstrates the usefulness of ground-based LIDAR in determining rockfall hazard ratings. It should be noted that all the pictures, point clouds, charts, hazard rating

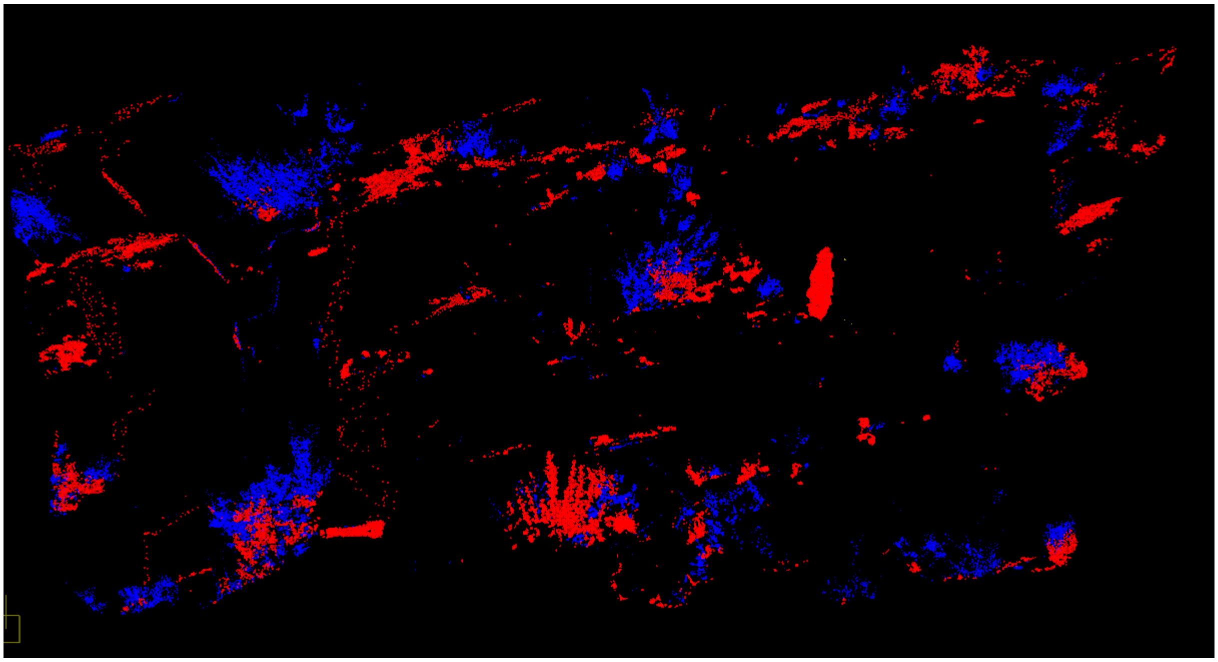
data sheet and analyses including the stereonet are contained in a single file (shown in Figure 15a) with a size less than 60 MB. LIDAR scanning at the site took less than two hours, and the determination of the rockfall hazard ratings were conducted with just a few hours of office time. As stated before, of the 15 parameters in the Utah system, 12 can be determined from LIDAR scanning and the remaining parameters are easily determined from traffic statistics, posted speed limits and AASHTO charts.

4.2 Change detection examples

Several change detection examples are shown here to demonstrate the usefulness of taking repeated scans at a site, even if the original scan locations are not known. The first two examples are scans taken of rock slopes along Mt. Lemmon Highway in southern Arizona. Originally the scans were taken over 5 years ago and the locations of the original scans are not known precisely. The first scan location is at mile marker 6, and the second scan location is at mile marker 8. Pictures of the two sites are shown in Figure 17a (taken April 2009 at the time of the re-scans). In both cases the rescans could be as far as 40 feet from the locations of the original scans.

The difference point clouds for the two sites are shown in Figures 17b and 17c. Red represents missing material and blue represents new material. In the site shown in Figure 17b, some new vegetation is clearly apparent in blue and some missing vegetation is clearly apparent in red. In terms of rock changes, there are some obvious boulders that have dislodged on the right side of the image. The volume of these boulders can be measured in the difference point cloud using the tools described in Section 3.1 and shown in Figure 6, giving a volume for the largest boulder of about 0.04 m^3. Also there appears to be missing material near the top of the slope even though this could be false change due to the difference in locations between the before and after scans. In the site shown in Figure 17c, there are red and blue outlines of many of the discontinuities, due to the before and after scans being taken from different locations. In spite of this noise, a large dislodged boulder is apparent in the mid-height and right part of the outcrop with a volume of about 2.1 m^3, and also some dislodged boulders (possibly scaled) are apparent near the bottom right of the image.

a)


b)

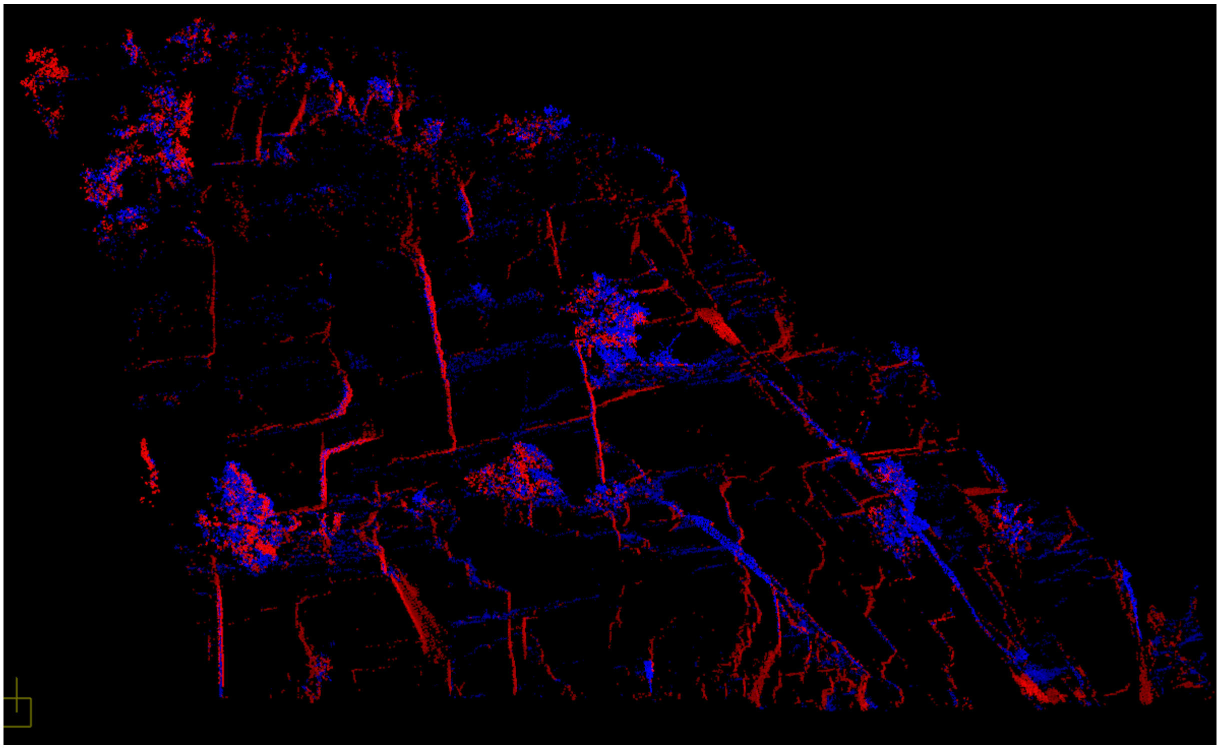
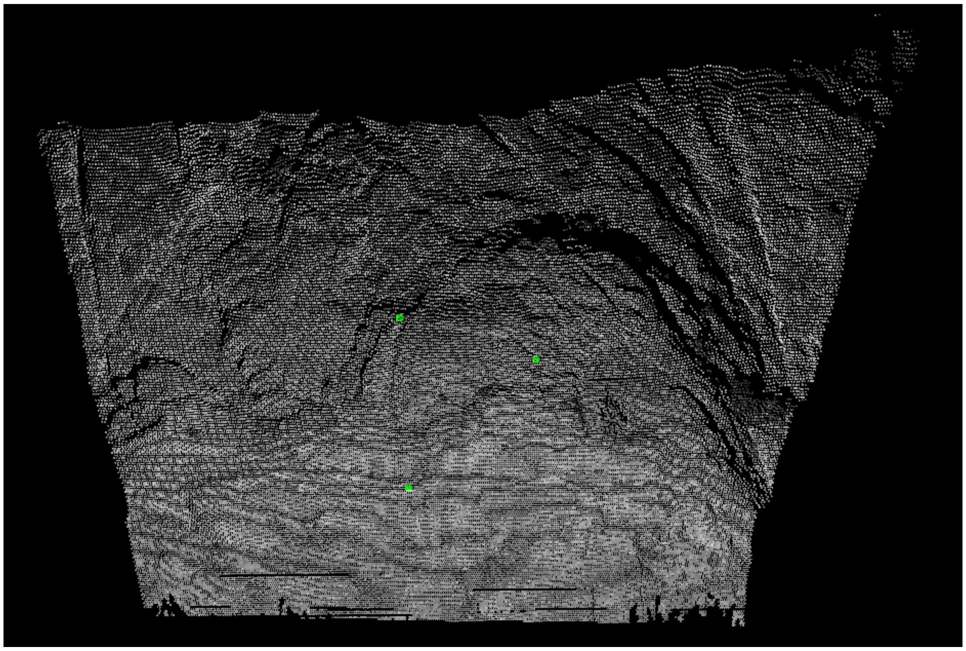

c)

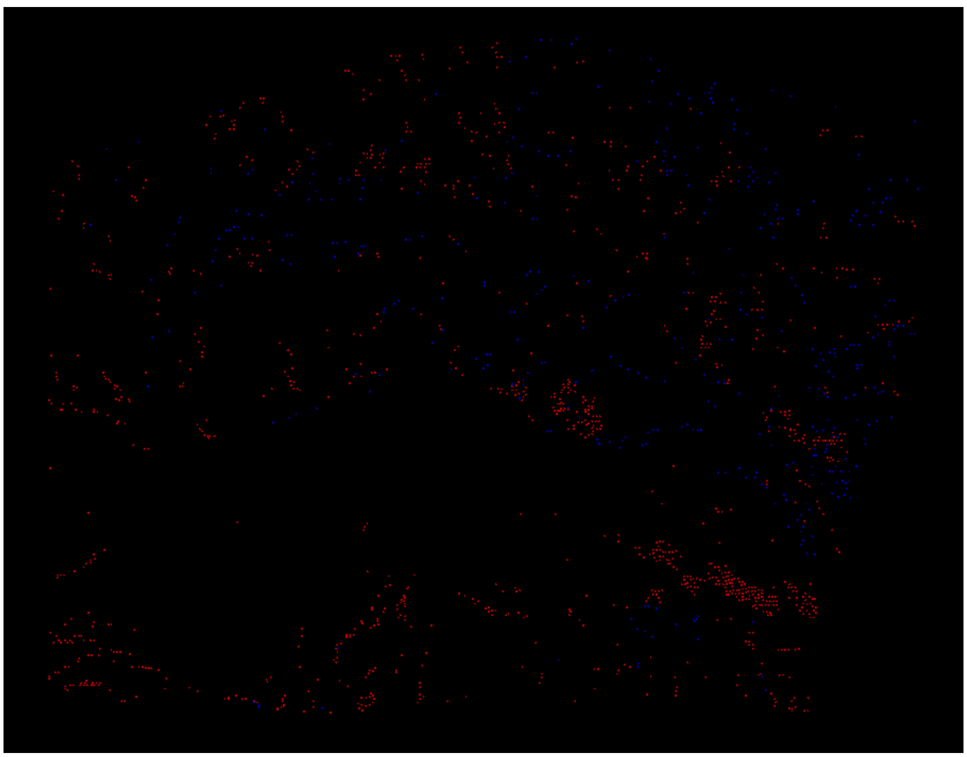
Figure 17. Rescanning of two sites along the Mt. Lemmon Highway near Tucson, Arizona. Original scans taken more than 5 years before and the locations of the original scans are not known precisely a) pictures of the two sites, b) and c) difference point clouds of the two sites.

The last change example is the north side of Interstate 70 near Georgetown, Colorado. This site was discussed in Section 3.2 and shown in Figure 11. Scans in this area were taken in 2006 and

then one year later in 2007. Figure 18a shows the “after” point cloud taken from station W12 in the Interstate 70 test area. Figure 18b shows the difference point cloud with blue indicating new material and red indicating missing material. Two red regions in the difference cloud indicate locations of possible rockfall. Figure 18c is a photograph showing the region scanned at station W12 (red rectangle) and also shows the location of the dislodged rock near the center of the scan (red circle). The volume of this dislodged rock block is calculated to be about 1.6 m^3.



a)



b)

c) 

Figure 18. Change detection along Interstate 70 at station W12, two scans taken one year apart. a) “after” point cloud, b) difference point cloud, c) photo showing scan region and location of possible dislodged boulder.

In summary, these change detection examples demonstrate the usefulness as well as some of the issues associated with using ground-based LIDAR for ground movement detection. Rockfall events can clearly be seen in all of the examples, but significant noise is also present in all examples. Some noise originates from uncertainty in the “before” scan location (which can be minimized by utilizing benchmarks or GPS to mark scan locations), some noise originates from vegetation, and some noise from the combined error from the before and after scans. The last source of noise will increase for large the scanning distances, make change detection a challenge for scan distances greater than 300 meters. Point cloud management is not a major problem with change detection, as the before, after and distance scans (as well as associated pictures and notes) all reside in the same file. For example, for the three examples shown in this section, the files were less than 30 MB. Additional software development is recommended to address some of the issues of noise and in interpreting the change results in terms of ground movement. This is discussed in Section 5 below.

5.0 General Discussion

The purpose of this research was to develop techniques and software tools for utilizing ground-based LIDAR for the identification and management of unstable highway slopes. The two primary applications of the research are 1) using repeated LIDAR scans at a site to locate and assess rockfall and other types of ground movement, and 2) using LIDAR scans to accurately determining rockfall hazard ratings. The examples shown in Section 4 demonstrate that both of

these LIDAR applications are feasible and useful. Also, for both applications, semi-automated point cloud processing algorithms have been developed to facilitate the analyses. It should be noted that this research was not intended to assess the feasibility of real-time monitoring of highway slopes using LIDAR technologies. This would involve fully automating the change detection analysis to determine if ground movement has occurred and then to possibly issue warnings if hazardous conditions are present. It also would involve permanently mounted LIDAR equipment with the ability to wirelessly transmit data. This is the subject of future research, as described in Section 6. Also, this report does not detail specific techniques for scanning highway slopes or for analyzing LIDAR point clouds for the purpose of rock mass characterization, which is adequately described in a recent FHWA report (Kemeny and Turner, 2008).

There are still issues remaining with the use of ground-based LIDAR for the purposes described above. Having high-resolution LIDAR scanning of hundreds of miles of highway slopes (including repeated scanning) would be extremely useful but both the scanning and the processing of the data would involve significant manhours. It makes more sense at the present time to focus on potentially hazardous slopes and conduct repeated scans of these slopes at a reasonable rate (say once a year). Even though this data cannot be used to predict immanent failure, this data would be extremely valuable for ongoing slope evaluation and for learning about the processes of slope deterioration and failure. In this research, the “difference” point cloud was used to evaluate the change between two successive scans, as shown in the examples in Section 4.2. However the difference point cloud is just the first step in evaluating ground movement. More software development is needed to interpret the difference point cloud in terms of the different types of possible ground movement (regions of ground moving, isolated rock block movement, erosion due to rainfall, new material appearing from outside the scan window, etc.). This research did not evaluate the many issues involved with the management of the point cloud data by transportation agencies. This research focused on the development of point cloud processing algorithms and the testing of these algorithms with field case studies. The management of the point cloud data involves the storage and management of potentially very large databases, and also the interface between different data formats and different software programs being utilized by transportation agencies. Even though this important subject was not covered in the current research, it is being covered in the ongoing Pooled Fund Project described in Section 6 below.

6.0 Plans for Implementation

There are a number of ways that the research described in this report will be disseminated and implemented. First of all, the results of the case studies that were conducted will be disseminated through future presentations and papers. Data collection and analyses are still ongoing at many of the sites discussed in Section 3.2. Another product of this research are the software enhancements to the Split FX program that will be marketed through Split Engineering LLC. Another outcome of this research is a new FHWA Pooled Fund project (TPF-5-166) being led by the Arizona Dept. of Transportation and subcontracted to the University of Arizona. This project started in January 2009 and will end December 2010. As part of this project, LIDAR scanning will be conducted in eight states (AZ, CA, CO, NH, NY, PA, TN, TX). The

focus is on the geotechnical evaluation of potentially unstable slopes, including change detection. An important aspect of this project is the management of the point cloud databases, and the interface between point cloud processing data and results, and other software and data systems being used by transportation agencies. A major deliverable of this project will be a draft "Recommended Practice" document for submission to and review by the American Association of State Highway and Transportation Officials (AASHTO). Finally, we have submitted a proposal to the National Science Foundation for the development of a real-time monitoring system for slopes based on a permanently mounted LIDAR-based instrument, which was discussed in Section 5.

7.0 Investigator Profile

Dr. John Kemeny is the Principal Investigator on the project. Dr. Kemeny is Partner and Co-Founder of Split Engineering LLC, a company that specializes in image processing software for the mining and geotechnical industries. Originally developed at the University of Arizona, the Split software analyzes digital images to determine the size distribution of rock fragments. Split Engineering was awarded Phase I and Phase II SBIR grants from NSF to develop and field test software for extracting rock mass characterization information from LIDAR scans (Split-FX). Dr. Kemeny has Ph.D. and M.Eng. degrees from the University of California, Berkeley, and B.A. degrees from the University of California, Santa Barbara. Dr. Kemeny is currently Professor in the Department of Mining and Geological Engineering at the University of Arizona. Dr. Kemeny has over 25 years of experience in rock mechanics and over 15 years experience with using new technologies such as digital image processing and LIDAR for rock engineering applications.

Brian Norton is the General Manager at Split Engineering, in addition to being a Partner and Co-Founder. Mr. Norton executes all aspects of general business management along with some operational activities in the company as needed, including managing Split-FX support. Mr. Norton earned his Master's in Business Administration from the Eller Graduate School of Management at the University of Arizona. He previously earned a B.S. in Business Administration from the University of Vermont.

Jeffrey W. Handy is Director of Development at Split Engineering and leads software development for the company. For the past eight years Mr. Handy has been developing scientific and engineering software. Mr. Handy joined Split Engineering in 2000 and currently specializes in software architecture and image processing and visualization techniques for three-dimensional raster and vector graphics.

Dr. James Donovan is Assistant Professor in the Department of Mining Engineering at the University of Utah. From 2003-2005 he was a Post Doctoral Research Associate with Split Engineering LLC in Tucson, Arizona. Dr. Donovan has Ph.D., M.S., and B.S. degrees from Virginia Tech. Dr. Donovan has a background in geomechanics, rock fracture mechanics, and advanced imaging techniques for rock mass characterization.

8.0 References

Badger, T.C. and Lowell, S. 1992. Rockfall Control Washington State. In Rockfall Prediction and Control and Landslide Case Histories, Transportation Research Record, National Research Council, Washington, No 1342, pp 14-19.

Bunce C.M., Cruden D.M and Morgenstern N.R. (1997) Assessment rock fall on a highway, Can.Geotech.J 34, pp 344-356

CDOT. 2005. I-70 Georgetown Incline, Final Rockfall Mitigation Feasibility Study, Project NO. 24-100, prepared for the Colorado Department of Transportation by Yeh and Associates, Denver, CO.

CDOT, 2007. http://www.dot.state.co.us/geotech/geotechphotos.cfm

Goodman, R. and S. Kieffer. 2000. Behavior of rock in slopes, J. Geotech. Geoenv. Eng., Vol. 126, No. 8, pp. 675-684.

Hadjin, Douglas J. 2002. New York State Department of Transportation Rock Slope Rating Procedure and Rockfall Assessment. TRB 02-3978, Geology and Properties of Earth Materials, Transportation Research Board, Washington D.C.

Kemeny, J., Norton, B. and K. Turner. 2006a. Rock Slope Stability Analysis Utilizing Ground-Based LIDAR and Digital Image Processing, Felsbau – Rock and Soil Engineering, Nr. 3/06, pp 8-15

Kemeny, J. and K. Turner. 2008. Ground-Based LiDAR: Rock Slope Mapping and Assessment, Report FHWA-CFL/TD-08-006, Federal Highway Administration Central Federal Lands Highway Division, Lakewood, CO.

Kemeny, J., Donovan, J. and C. Rodríguez. 2006b. Application of Ground-Based LIDAR for Pre-Blast Rock Mass Characterization, Proceedings of Fragblast 8, the 8th International Conference on Fragmentation by Blasting, Santiago, Chile.

Kemeny, J., Turner, K. and B. Norton. 2006c. LIDAR for Rock Mass Characterization: Hardware, Software, Accuracy and Best-Practices, Proceedings of the Workshop on Laser and Photogrammetric Methods For Rock Mass Characterization: Exploring New Opportunities, Golden, CO.

Kottenstette, J.T. 2005. Measurement of Geologic Features using Close Range Terrestrial Photogrammetry, The 40th U.S. Symposium on Rock Mechanics (USRMS): Rock Mechanics for Energy, Mineral and Infrastructure Development in the Northern Regions, held in Anchorage, Alaska, June 25-29, 2005.

Leica. 2008. www.leica-geosystems.com

Pack, R., Boie, K., Mather, S. and J. Farrell. 2006. UDOT Rockfall Hazard Rating System: Final Report and User's Manual, Utah Department of Transportation report UT-06.07.

Pierson, L.A. , Van Vickle, R. Davis, S. A. 1990. The Rockfall Hazard Rating System Implementation Manual. Oregon State Highway Division. FWHA-OR-EG-90-01. Washington D.C. Federal Highway Administration.

POB. 2007 Point of Beginning 2007 Laser Scanner Survey, http://laser.jadaproductions.net/

Schuster, R.L., and R.W. Fleming. 1986. "Economic Losses and Fatalities Due to Landslides." Association of Engineering Geologists Bulletin. Vol. 23, No.1, pp. 11-28.

Split Engineering. 2008. www.spliteng.com