Using LIDAR in Highway Rock Cuts

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ABSTRACT

LIDAR is a relatively new technology that is being used in many aspects of geology and engineering, including researching the potential for rock falls on highway rock cuts. At Missouri University of Science and Technology we are developing methods for remotely measuring joint orientations and quantifying the raveling process. Measuring joint orientations along highways remotely is safer, more accurate, and can result in larger and more accurate data sets, including measurements from otherwise inaccessible areas. Measuring the nature of rock raveling will provide the data needed to begin the process of modeling the rock raveling process.

INTRODUCTION

LIDAR(LIght Detection And Ranging) is a relatively new technology that is being used in many aspects of geology and engineering. At Missouri University of Science and Technology we are developing methods for remotely measuring joint orientations and quantifying the raveling process, in addition to many other measurement capabilities. We are using LIDAR to measure discontinuity orientation (which governs certain types of instabilities) and to measure and research the rock raveling process (which in some jurisdictions is the major cause of instability in highway rock cuts.)

ROCK FALLS ON HIGHWAYS

Rock falls are a major geological hazard in many States with mountainous or hilly terrain. The safety and convenience of the motoring public demands that highway rock cuts be made as safe as possible, while expenditures on remediation are always limited by often shrinking budgets. Catastrophic failures of rock cuts can result in property damage, injury, and even death. Highways impeded by even small spills of rock material are an inconvenience for motorists. Rock fall hazard assessment in the USA has traditionally been a reactive process.
Highways that traverse through rocky terrains often require that artificial vertical slopes be cut by blasting techniques to facilitate the highway construction. A constant danger to the motoring public is for large blocks of rock to fall or slide down, at worst killing and injuring members of the motoring public, and at best blocking the highway and impeding traffic flow.

Discontinuity Controlled Rock Falls (Conducive to Quantitative Analysis)

Many of these failures result because of release along planar cracks or discontinuities in rock mass. Whether or not failure occurs will depend on the orientation of the cracks, individually or in combinations (Figure 1).The cracks or discontinuities tend to cluster in terms of their orientations, into typically three or more sets, which tend to be mutually orthogonal, or roughly at 90 degree to each other (Figure 2). Knowing the orientations of the discontinuities can lead to stability prediction based on well established analytical tools (Hoek and Bray, 1981).

Figure 1. Example of wedge, planar, and toppling failures along road cuts.

Figure 2: Orthogonal nature of joint sets. Measurements of the “cracks” or discontinuities are displayed in Figure 3.

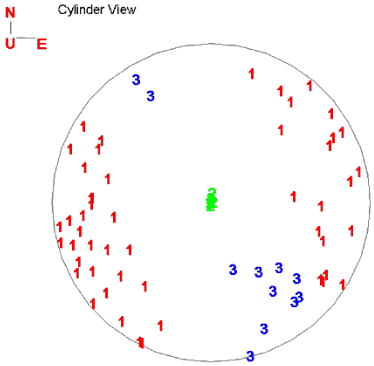


Figure 3. Projections of vectors normal to discontinuity plane on a unit lower hemisphere, clustered into three sets.

Figure 3 shows the time honored stereonet projection method [2] where each data point, consisting of a normal vector to an individual discontinuity plane, is assigned to a discontinuity set by using cluster analysis. Cluster analysis techniques are described in [3,4,5,6,7].

The orientations can be and have been traditionally measured using manual compass and clinometer methods. These methods are however slow, tedious and cumbersome, are in some cases dangerous because of potential falling rock, and are often limited to easily accessible locations like the base of the slope.

Once having identified the discontinuities traditional graphical or computational techniques can be used to determine the kinematic feasibility of failure (Figure 4) and standard modeling techniques such as limiting equilibrium analysis can be used to determine if failure will indeed take place (Figure 5) [1,8,9,10,11,12,13,14, 15,16,17].

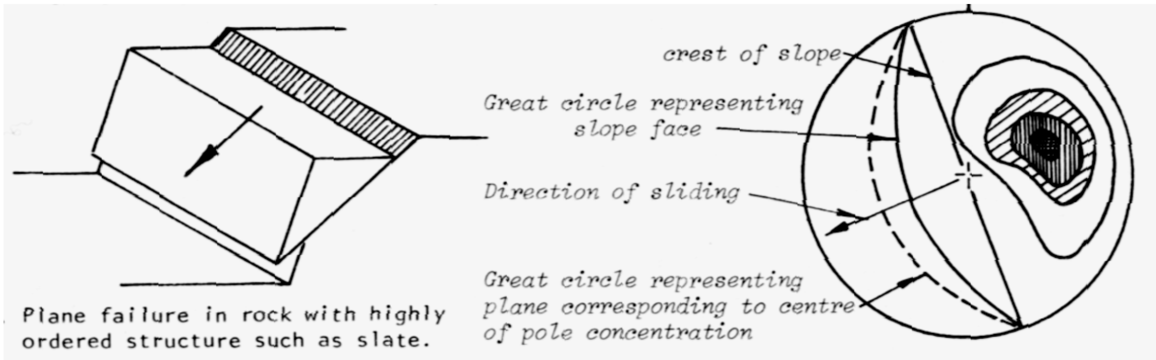


Figure 4: Planar failure geometry (left) and graphical method of determining if slide failure is kinematically possible (Hoek and Bray, 1981).

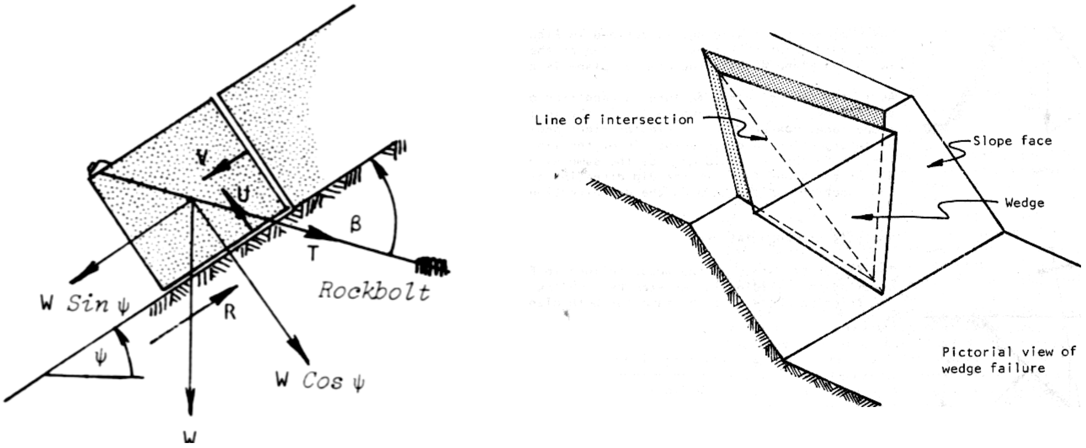


Figure 5: Limiting equilibriums analysis applied to planar features (left) and wedge features (right) after Hoek and Bray, [1].

Raveling Type Rock Falls (Not Conducive to Quantitative Analysis)

In many terrains the discontinuities are not oriented in such a way that they contribute to create wedge, planar sliding, or toppling failures or other easily analyzed failure mechanisms. Franklin and Senior [18] report that of 415 analyzed cases of failure in Northern Ontario, only 33% of failures involved these mechanisms (23% toppling, 8% planar sliding, 2% wedge sliding).

In the Northern Ontario study, 65% of the failures were of the “raveling” type. These included raveling (25%), overhang/undercutting failure (15%), ice jacking (14%), and rolling blocks (11%). In other terrains, most notably flat lying sedimentary rock, such as is found in much of the US, the predominant failure mechanism being of the raveling type is even greater.

Raveling failure, the most common type of rock failure is poorly understood. Analysis is mostly descriptive, and prediction of the amount of raveling is typically an empirical exercise in guessing based on extrapolation of visual evidence. Raveling failures are often usually slow and time dependent, but can also be catastrophic if they involve large blocks falling or many blocks releasing at once. Large blocks are often results of the collapse of overhanging ledges that have been undercut by raveling.

The literature abounds with mention of raveling [1,8,19,20]. Rock hazard rating systems use raveling as a parameter to determine the durability of rock cuts [21,22,23]. European research has investigated the processes and morphology of raveling, although in a qualitative observational way [23,24,25].In short there is no quantitative mechanism and model available to describe the raveling process, and consequently no predictive tools. Mitigation efforts make use of empirical observation and engineering judgement.

Figure 6.Example of raveling, undercutting, and rolling failures along road cuts.

TERESTRIAL LIDAR TECHNOLOGY

As a distance measuring device, LIDAR replaces traditional methods of laser surveying, which take individual measurements, and require reflective targets to measure distances and angles. LIDAR is more analogous to radar, in that the scanning laser can make thousands ofpoint measurements per second, reflecting off any surface, and returning a point cloud, which can be used by sophisticated software to create a very detailed 3-D surface map. The scanner uses either time of flight or phase shift sensors technology. The result is a million of points reflected from the surface. The points are represented by xyz coordinates, these xyz coordinates and their associated intensity values are known as a “Point cloud”. At Missouri S&T we have two LIDAR scanners (Figure 7). The Leica ScanStation II is a time of flight scanner capable of scanning up to 300 m at a maximum rate of 50,000 points per second. The Leica HDS6000 is a phase shift scanner capable of scanning up to 100 m at a maximum rate of 500,000 points per second. Both scanners have an accuracy of a bit less that 1 cm for a single measurement, but accuracy can be improved up to an order of magnitude for modeled surfaces, and even greater for in special circumstances. The ScanStation II in addition has a built in camera, so is capable of adding optical color information to the point cloud.

Figure 7: Left: Leica ScanStation II time of flight scanner with integrated optical camera. Right Leica HDS 6000 phase shift scanner on remote controlled robotic buggy.

Kemeny et al. characterized rock masses using LiDAR and automated point cloud processing, and also analyzed rock slope stability using LiDAR and digital images [27, 28], including measuring and clustering discontinuity orientations. LiDAR was used by Mikos et al. to study rock slope stability [29]. Lim et al used photogrammetry and laser scanning to monitor processes active in hard rock coastal cliffs [30]. High resolution LiDAR data was used by Sagy et al. to quantitatively study fault surface geometry [31]. Enge et al. illustrated the use of LiDAR to study petroleum reservoir analogues [32].

LIDAR DISCONTINUITY ORIENTATION MEASUREMENTS

To measure joint orientations LIDAR scans are taken of the joints to be measured (Figure 1). To simplify and speed up the process, no survey control is needed; it is simply required to measure the strike of a single sub-vertical feature in the scan. In addition, since only a single LIDAR scan is sufficient, no image registration is required. (In the case of the Leica ScanStation II, the optical image is automatically registered to the scanned point cloud.)Two types of rock faces/cuts are possible (Figure 8). In the first case some rock faces are composed almost exclusively of natural discontinuity surfaces. The orientation of each of these surfaces can be and should be measured. These are conducive to automatic or semi automated analysis such as described in [32,33,34,35,36,37,38]. Figure 9 shows an example of an automated analysis of such a rock face, in which the discontinuity measurements are clustered into sets and each resulting set is represented by a different color.

Figure 8: Left: Rock faces with 100% coverage of natural joint surfaces. Right:Rock faces with significant ambiguity as to the location of natural joint surfaces.

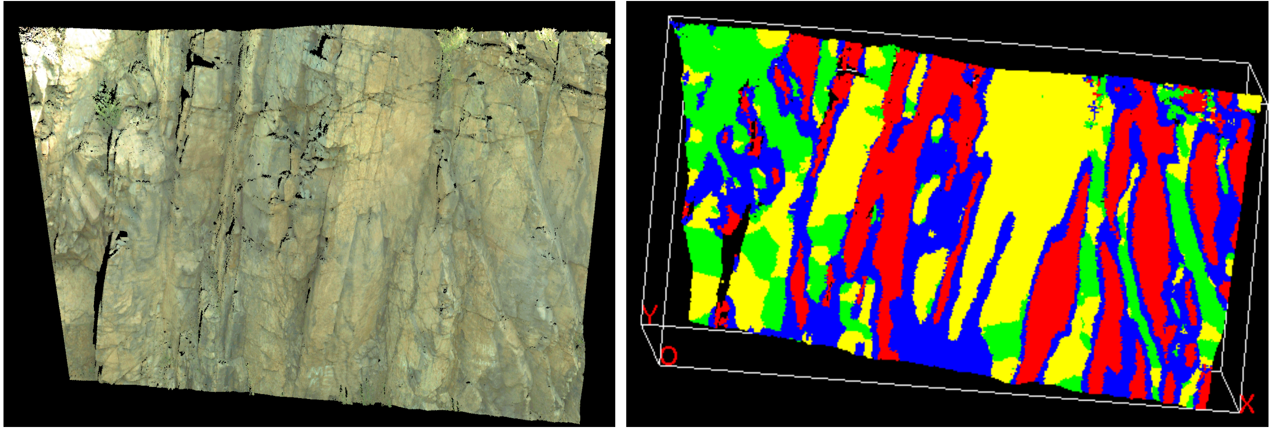


Figure 9: Left:Point cloud of a Missouri Rock cut in ignimbrite rock. Right: Identification of discontinuity orientations. Each different color represents discontinuities of similar orientations.

On the other hand for rock cuts that have sparse representation of natural joint surfaces, it is often easiest just to manually identify individual discontinuities on a LIDAR image viewer and pick (on the planar discontinuity surface) three co-planar non co-linear points. Figure 10 shows an example of using a point cloud viewer to select 3 points on a discontinuity surface. The discontinuity orientation can be determined by the classic 3-point solution [39].

Figures 11-12 show the results of a small verification study where LIDAR measurements are compared with manual measurements using a Brunton compass.

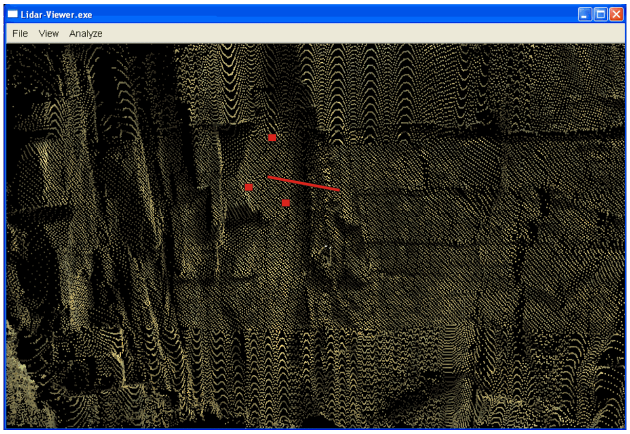
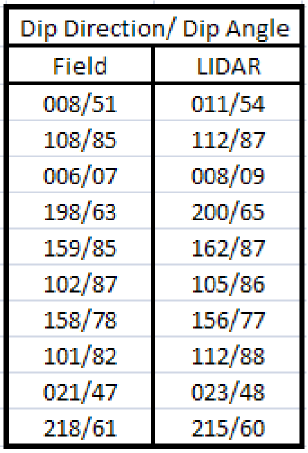


Figure 10: Picking three points on a discontinuity surface to calculate orientation.

Figure 11: Rock cut selected for verification study.



Dip Direction/ Dip Angle	
Field	LIDAR
008/51	011/54
108/85	112/87
006/07	008/09
198/63	200/65
159/85	162/87
102/87	105/86
158/78	156/77
101/82	112/88
021/47	023/48
218/61	215/60

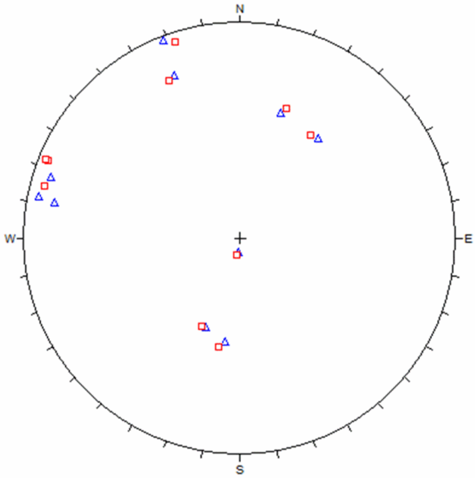


Figure 12: Results of verification study comparing manual measurements with LIDAR measurements. On the lower hemisphere projection, red points are LIDAR measurements, blue points are manual measurements.

RAVELING MEASUREMENTS

To quantify raveling of rock,scans of a raveling rock face are taken over a period of time. Again,to simplify and speed up the process, no survey control is needed, it is simply required to position the LIDAR unit in approximated the same place, and scan approximated the same area. Algorithms for automated registration are used to superimpose the two scanned sets, and then the volume differences between the two sets are measured and displayed. Figure 13 shows an example of a raveling rock cut in weathered dolomite. Figure 14 shows the results of 3 sequential measurements with the missing pieces highlighted for a six month pilot study.

Figure 13: Scan section of a rock face near a local quarry.

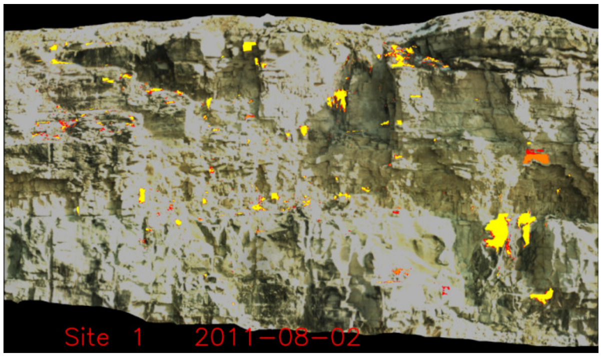


Figure 14: Point cloud of the scan and measured progressive raveling loss. Yellow, 7-15, orange 7/26, red 8/02.

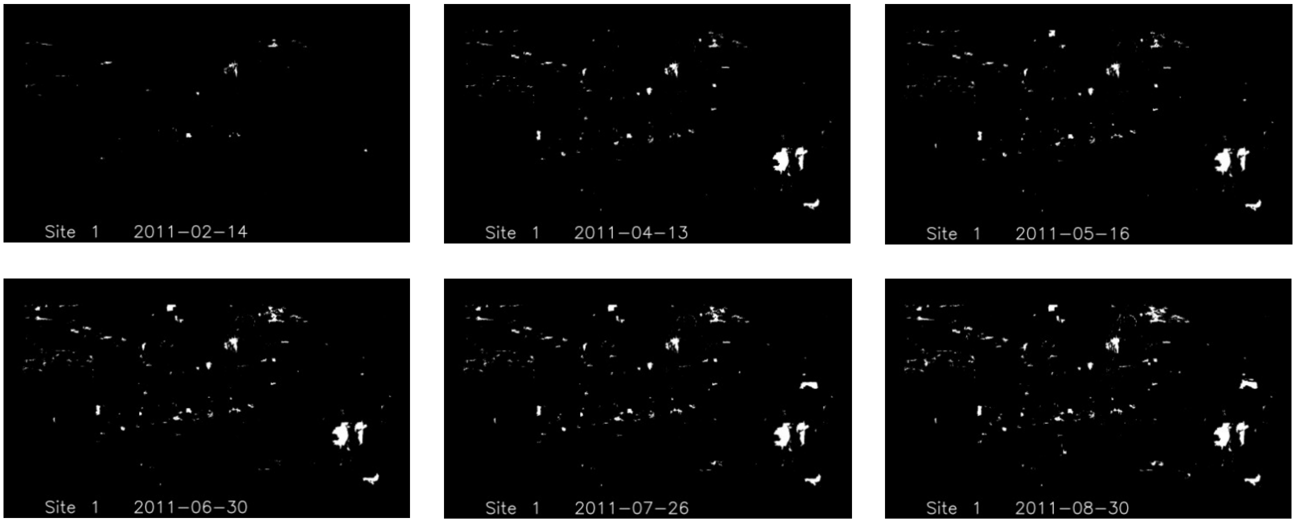


Figure 15.Part of the sequence of 16 images showing the increase in missing (fallen) blocks as a function of time.

To demonstrate the feasibility of the proposed technique, a small 6 month study was undertaken (Figure 15). Two small local rock cuts one in and one near a local quarry were imaged using LIDAR, 18 separate times over that period. At the same time measurements of rainfall and ground vibration from blasting were taken. Resolution was found to be 3 mm for site one and 8mm for site 2, with an average of 6.7 million data points per scan. The smallest rock that could be detected is 9 mm across.Software was developed to register the point clouds (with an average root mean square error of 2.5 mm) scanned at different times and measure the volume of the fallen rock. All software is developed in C++, compiled using the GNU G++ complier, and runs on Ubuntu® Linux. The processing sequence was as follows:

1. Pre-loading, determines the minimum and maximum ranges of the horizontal and vertical components of the observation set.
2. Load individual triplets (x,y,z), sort according to position.
3. Filling gaps by interpolating between triplets.
4. Register the image to know coordinate system using automatic algorithms.
5. Determine maximum common crop boundary for all temporal data sets
6. Crop the image so that each image consistently covers the same area.
7. Removal of vegetation and all non-rock artifacts.
8. Creation of a difference surface between any two scans.
9. Segmentation of individual (missing) rocks.
10. Volume calculation.

Preliminary correlations (Figure 16) between volume of blocks lost and freeze-thaw cycles, blasting episodes, and rainfall are somewhat tentative at this point. Site 2 seems significantly affected freeze-thaw cycles in correlating scan #2. In the area of scans #11-13, as the rainfall decrease to near zero the volume of blocks lost also trends to zero. Unanswered at this point is why the difference in scan #2 between the two sites which are very close together.

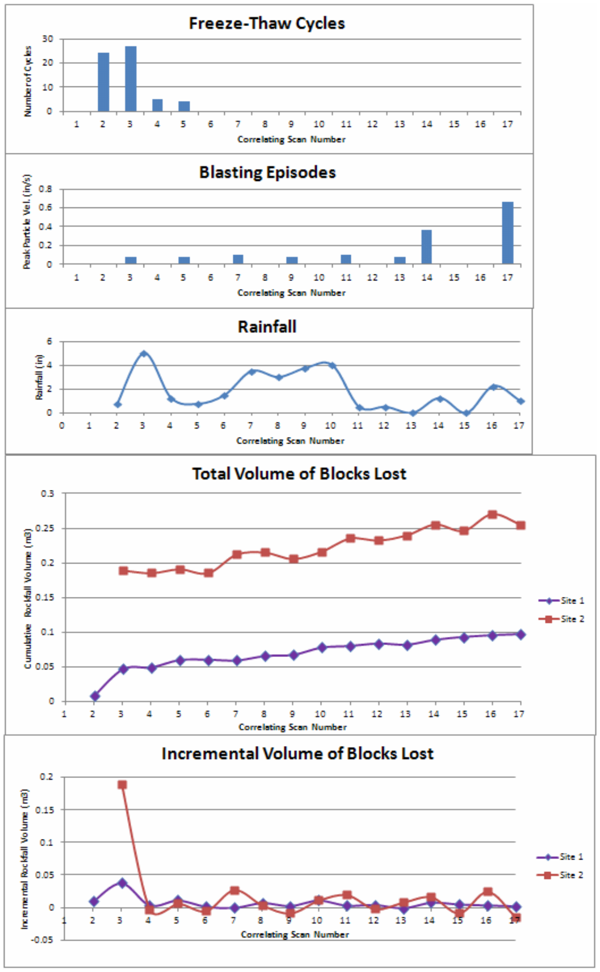


Figure 16: Results of the study: Correlation between volume loss and external stimuli including rainfall, freeze-thaw cycles, and the number of blasting episodes in a nearby quarry.

The results show that in some incremental scans there were some small volume gains. Observations suggest that this is real, and it is a result of small quantities of rock accumulating on ledges after having fallen from higher up. More work on the algorithms may increase the fidelity of the lost volume measurement.

Ultimately the goal of this work is to provide verification for numerical models that will be used to model the raveling process.

CONCLUSIONS

LIDAR technology provides tremendous new opportunities for measurement and characterization of rock cuts. Measurements using LIDAR are superior to manual measurements and older technologies in that they produce vast amounts of data, quickly, safely and with less sampling bias. What is required are algorithms, both simple and sophisticated, that use the LIDAR data to characterize the rock cuts and provide input to predictive tools.

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