CHAPTER 7 – CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

In this final report the use of ground-based LiDAR (also called 3D laser scanners) to obtain highway rock slope geotechnical information has been reviewed. This included discussions of currently available LiDAR hardware and software, the current state of LiDAR for highway geotechnical applications (rock mass characterization, rockfall characterization, as-built 3D measurements), best-practices for field scanning and for point cloud data processing, and expected trends in the industry in the near future.

At the beginning of this report a "wish list" was given of benefits that a new technology should possess in order to be useful to FHWA for highway rock slope stability studies. Conclusions are now made for each item on the list with regards to the use of ground-based LiDAR.

Automatic data acquisition over entire slope

It was demonstrated in Chapter 4 that some of the most important types of geotechnical information that is currently being collected by hand can be acquired from LiDAR point clouds and associated digital images. This includes detailed information about rock discontinuity orientation, roughness, length, spacing and block size. In many cases, this information can be automatically extracted from LiDAR point clouds using currently available point cloud processing software. For example, using the Split FX software, discontinuities in a point cloud can be automatically delineated and the orientations plotted on a stereonet. This information can then be exported to rock slope stability software. It was also demonstrated in Chapter 5 that fracture orientation errors of less than one degree could be achieved if at least three surveyed targets are used as part of the scanner registration. Currently, the determination of discontinuity roughness, length, spacing and block size is semi-automatic and involves the use of hand editing tools in the point cloud processing software.

Remote data acquisition for improved safety

Ground-based LiDAR collects data at a safe distance from the slope. Most of the ground-based LiDAR units now available have the ability to scan slopes from a distance of at least 50 meters, which is sufficient for many highway slope applications. Many scanners have a range of up to 200 meters and a few scanners have a range of 1 km or more. Details on scanner range are provided in Appendix A. Data collection for scanner registration (surveyed targets, backsighting, or scanner orientation measurements) can also be conducted at a safe distance from the slope.

Rapid data collection

A typical scan of a 20 m high by 30 m wide highway slope with a time-of-flight scanner takes about 10 minutes (assumes 2 cm point spacing and 2500 points per second). This same scan with a phase-shift scanner would take less than 20 seconds (assumes 2 cm spacing and 100,000 points per second). Additional time in the field is required to collect data for scanner registration. Depending on the method for scanner registration, this can take as little as a few extra minutes. Processing the data to extract geotechnical information can also be conducted very rapidly. It was shown in Chapter 4 that automatically delineating the fractures in a point cloud and plotting the orientations on a stereonet takes only a few minutes. A complete analysis, including the extraction of discontinuity roughness, fracture length and spacing, block size and photo draping can be conducted in several hours.

New technologies for data collection and processing easy to learn and operate

3D laser scanners are very easy to operate, as discussed in Chapters 2 and 5. Most scanners have a very user-friendly interface and only require a few settings before scanning, such as the scan region of interest, the point cloud spacing, and the camera exposure parameters. Appropriate personnel to conduct field LiDAR surveys could include field technicians, field surveyors, geologists and geotechnical personnel. Processing point clouds to extract geotechnical information using point cloud processing software is also fairly easy to learn but does require some geotechnical expertise. Users need to have a basic understanding of rock engineering principles associated with rock masses and rock discontinuities.

Able to provide a high-resolution 3D Digital Terrain Model (DTM) of a highway slope or rock outcrop that could be compared with future DTMs as the slope ages and deteriorates

An important feature of ground-based LiDAR is the ability to drape a high-resolution digital image onto a point cloud, producing a high resolution, 3D DTM of the scanned slope. This DTM represents a 3D snapshot of the slope at a particular time, which can be compared with DTMs taken a later time. Point clouds taken at different times, for instance, can be subtracted to produce a difference point cloud. As described in Chapter 4, the difference point cloud can be used to analyze rockfall, slope weathering, or the volume change after rock excavation.

Cost Effective

It was shown in Chapter 5 that 3D laser scanning can be very cost effective compared with traditional scanline mapping and photogrammetric surveys. Even though LiDAR hardware is expensive, the cost of the hardware can be shared between different uses and different offices. Scanner rental is also an option. Point cloud processing software is relatively inexpensive and in many instances is less expensive than photogrammetric software.

Overall Conclusions

It is concluded that there are many benefits to using ground-based LiDAR to assist with highway rock slope stability studies. Specific recommendations with regards to utilizing ground-based LiDAR for highway slope stability projects are given below.

RECOMMENDATIONS

Field Scanning

Field LiDAR surveys can be conducted by either FHWA personnel or outside surveying contractors. In either case, the best practices described in Chapter 5 should be followed closely, along with the documented procedures for the particular scanner that is used. With regard to scanner registration, there are three primary choices, as listed below:

1. Three or more surveyed targets in the scanned scene.
2. Backsighting to known benchmarks to establish the scanner position and and scan direction
3. Using a compass to establish the scan direction (normally by measuring the bearing and tilt of the scanner itself)

If established benchmarks are available at the location where scanning is to be conducted, then either method 1 or 2 is recommended, since they result in a more accurate registration than method 3. Method 3 only takes a few minutes and can be used as a backup registration method. Method 3 can be used as the primary method when benchmarks are not available, or when scanning and scanner registration must be conducted very quickly.

Point Cloud Processing Software

Data processing using point cloud software is relatively straightforward, however it is recommended that the personnel involved with LiDAR data analysis have training in rock engineering principles and design. Data processing using point cloud software can be conducted by either FHWA personnel or outside consultants. Either way, the best practices described in Chapter 5 should be followed. At the present time, only the Split FX software is designed specifically for extracting geotechnical information from LiDAR point clouds, and its use is recommended at this time. In the future, other software packages may also have these capabilities. Even though all examples shown in this report were conducted using the Split FX software, much of the analysis could be conducted with the more generic point cloud processing or CADD software. However, this is not recommended since it will involve significant manhours in software training and processing (finding hundreds of fracture planes in a point cloud by hand, for instance, could take an order of magnitude more time than utilizing automated methods).

Additional Recommended Studies

There are several areas that warrant additional research and case studies, as described below.

Comparing Scanner Registration Methods

As listed above, there are three primary methods for scanner registration, and each method has specific procedures and issues. A detailed case study should be conducted to determine the advantages and disadvantages of each method. Also, the specific accuracies of each method should be determined for a variety of field conditions, as well as determining best practices for each method to optimize accuracy and the time spent in the field.

"Start to Finish" Case Study for Rock Slope Stability

As a full assessment of the procedures described in this report, a "start-to-finish" slope stability case study should be conducted for a specific highway slope. This would include conducting a LiDAR survey of a slope, extracting geotechnical parameters, conducting a slope stability analysis, and writing a report on the results. Many case studies have been conducted using ground-based LiDAR in many different rock types. These case studies have evaluated different aspects of utilizing LiDAR for rock slope stability, but no single case study has evaluated all the field and processing procedures involved. Also, no case studies have been conducted with close collaboration with FHWA personnel and procedures.

Extracting Additional Information From LiDAR Point Clouds

There is the potential to extract additional information from LiDAR that would be useful for rock slope stability studies. This additional information includes:

- Degree of slope weathering (slight, moderate, significant)
- Discontinuity fill (mineral composition of fill and thickness of fill)
- Geology (mineral composition)
- Slope movement (slope displacement, velocity and acceleration)
- Incorporation of slope stability equations in point cloud processing software (allows slope stability visualization on point clouds)
- Automation of the extraction of information currently extracted using hand tools (roughness, length and spacing distributions, block size)

It is recommended that research be conducted in the areas described above.