CHAPTER 5 – BEST PRACTICES

As hardware and software solutions are being developed for rock mass and rockfall characterization using LiDAR and digital image processing, guidance is needed on specific and appropriate procedures involved to conduct ground-based LiDAR surveys, as well as the appropriate data validation, processing and management procedures. In the field, appropriate procedures must be specified concerning a) the suitability of a site for LiDAR surveying, b) the procedures for scanning (number of scans, point spacing, resolution, etc.), c) establishing surveying control points, d) taking digital images, and e) collecting non-digital types of information. After a survey is conducted, data processing and management procedures include a) the specific steps that should be taken to process the data using various software packages for specific outcomes (i.e., calculate the slope hazard at a particular site), and b) the appropriate standards and formats for managing and archiving the various kinds of data from a LiDAR survey, including the raw scanner files, point cloud files, rendered surface files, and calculations and interpretations made on this data.

Based on a number of case studies that have been conducted in the past several years (some of which were described in Chapter 4), recommendations for best practices for the topics mentioned above are made, as discussed below. It should be noted that the development of best practices is an ongoing activity, and the recommendations made in this section will change with time. This chapter concludes with sections on the cost of a LiDAR survey, the accuracy of LiDAR generated data, and a brief comparison of LiDAR and photogrammetry for obtaining geotechnical data.

BEST PRACTICES IN THE FIELD

The basic procedure for scanning in the field was described in Chapter 2. Now some detailed recommended procedures are presented.

Deciding on Scanner Placement and Number of Scans

One of the first and most important steps is to spend a few minutes at the field site to determine where the scanner will be placed and how many scans will be made. For scans of a slope adjacent to a highway, scans will most likely be made on the opposite side of the highway, along a turn-out or shoulder. In general, it is best if the distance from the scanner to the slope is at least as great as the height of the slope of interest, as shown in Figure 23. This eliminates a sharp angle between the scanner field of view and the dip of the slope. If the height of the slope of interest is higher than approximately 30 m (98 ft), then the optimum location for the scanner will be farther away than the other side of the highway, which could present access and viewing problems depending on the topography and landowner issues. Another parameter is the distance between scans taken along the highway. In general it is best if the scanner horizontal field of view is 50 degrees or less, as shown in Figure 23. This eliminates a sharp angle between the scanner field of view and the strike of the slope. Also, at least a 20% overlap between scans should be maintained, as shown in Figure 23. The overlap is used to assist with the stitching together of point clouds.

A final decision is whether multiple scans of a face taken at different angles should be made. Depending on the orientation of discontinuities relative to the scanning direction, it is possible that a joint set will be obscured (in the scanner shadow zone, as discussed in Chapter 4). If the guidelines given above are followed, the chance of significant scanner shadow zone is minimized. Also, a joint set that is subject to scanner shadow zone is likely to show traces, from which the orientation can be picked up with tracing on a draped photo as shown in Chapter 4. However, it is important to evaluate each scanner site for possible shadow zone, and take multiple images if necessary. For instance, referring to Figure 23, if Scan 2 has a potential problem with scanner shadow zone at Face 2, then either the locations of Scan 1 or Scan 3 can be used to take an additional scan of Face 2.

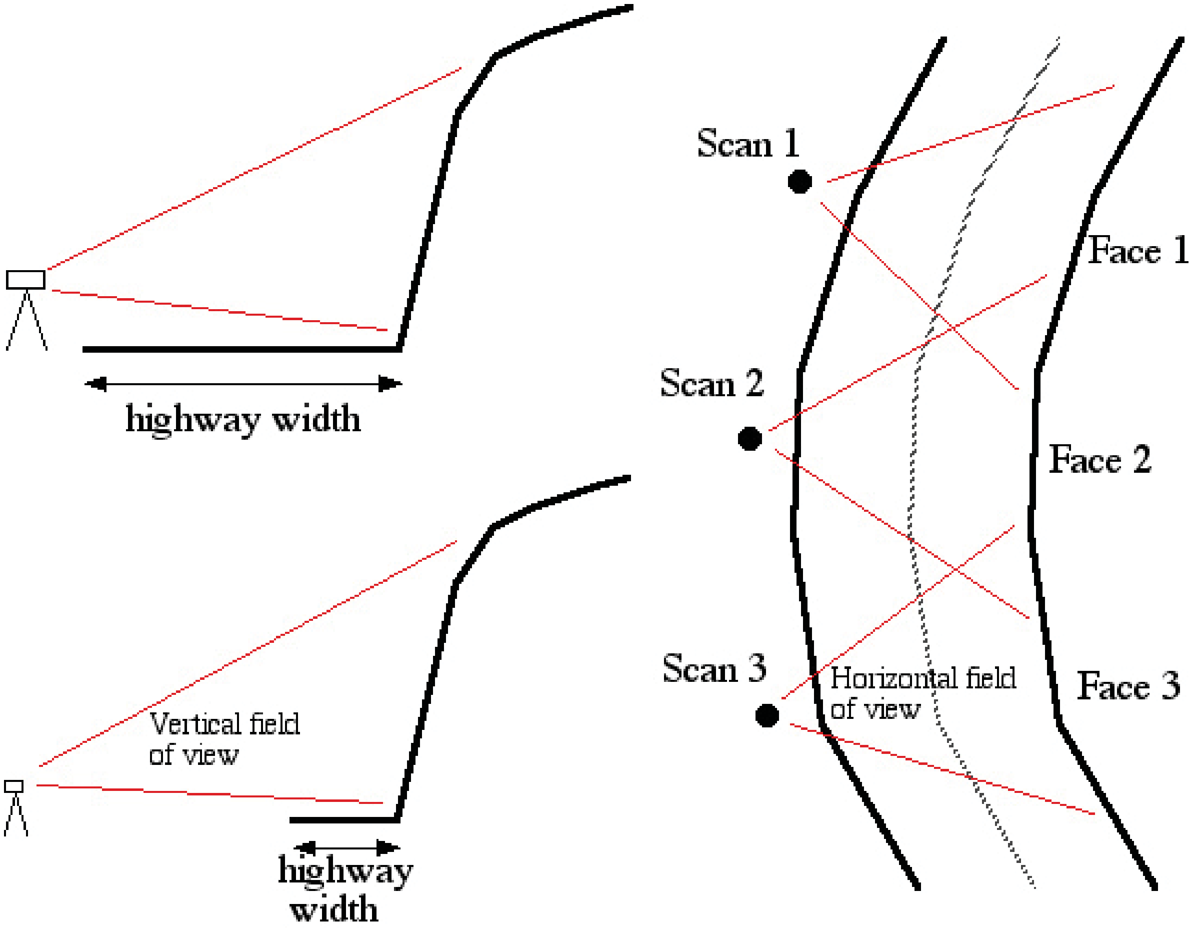

Figure 23. Schematic. Figures on left show cross sections with recommended scanning distances depending on the height of the slope of interest. Figure on right shows plan view with recommended distances between scanning locations.

In most cases, multiple scans of a face at different angles will not be necessary, particularly with the use of photo draping to extract discontinuity orientation from fracture traces. However, if time warrants, and if the site conditions are complex and/or high risk, then taking multiple scans to eliminate potential scanner shadow zones is recommended.

Deciding on the Method for Scanner Registration

The next important step is to decide how scanner registration will be conducted. All scanners are able to register a point cloud by having at least three targets of known position in the scene. The three or more targets should not be in the same plane, and having targets across all areas of the scene produces the best results. Another procedure is to register some of the scans using targets, and register others by "stitching" them with those that have been registered (the stitching uses an Iterative Closest Point algorithm and is available in several of the point cloud processing programs). Some scanners can be registered by backsighting to known benchmarks along with surveying in the location of the scanner. Backsighting uses a built in optical telescope to site to known points so that the orientation of the scan can be determined. Finally, the orientation can be registered by carefully measuring the orientation of the scanner (if the scanner is leveled this only involves the measurement of scanner bearing). This last method, along with an accurate GPS of the scanner origin (sighting over a known benchmark, for instance), will also give the full registration. It should be noted that none of the above methods involve putting targets on the rock slope itself. Putting targets on the slope is a safety hazard and should be avoided, particularly on unstable slopes. However, depending on specific site conditions, putting targets on the slope may have advantages if it improves the accuracy of the registration and can be conducted in a safe manner.

At the present time, there are no recommendations on the preferred method for scanner registration. One reason is that the recommended method depends on the type and model of scanner. Backsighting, for instance, is only available in some of the scanners. Several publications are available looking in detail at the accuracy of various methods of scanner registration (Reshetyuk, 2006, for instance), the details of which are beyond the scope of this report. Several studies have been made by the author to compare different methods for scanner registration, but the results from these studies are not available at the present time.

Scanner Field of View and Point Spacing

In order to get a uniform point spacing in the point cloud, follow the guidelines as given in Figure 23 for the scanner field of view. Figure 24 shows a point cloud taken with a Riegl scanner, which has a 360-degree field of view. It shows a very high density of points near the scanner, with a much wider spacing farther away from the scanner. Shown in green is the only area of the point cloud that should be analyzed. It represents the rock face of interest (not things on the other side of the highway of no interest) with the field of view following the guidelines shown in Figure 23.

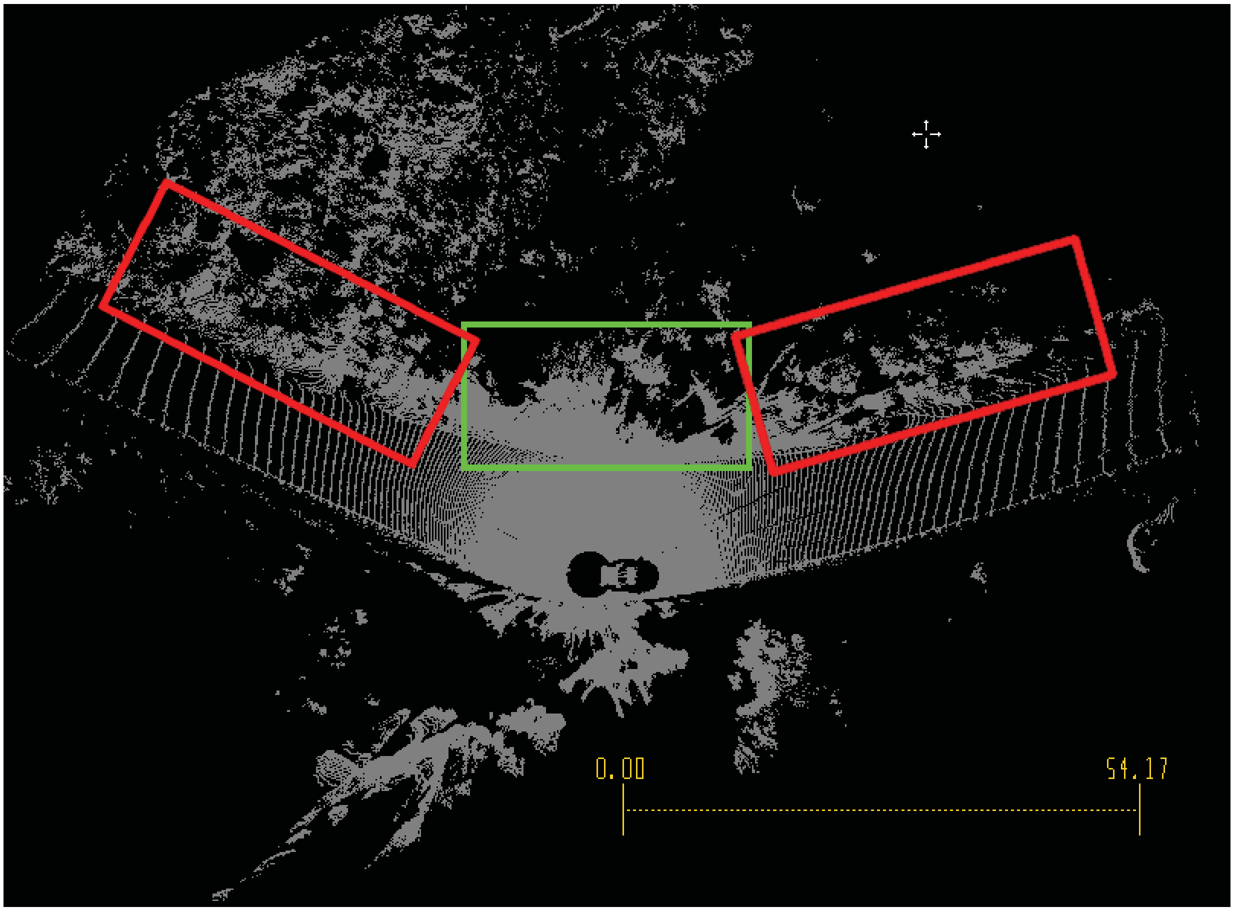

Figure 24. Schematic. Point cloud example. Plan view of scan of Mt. Lemmon Highway, Milepost 15. Proper scan window shown in green, unsuitable scanned highway slopes shown in red.

The areas shown in red are also of the rock face of interest, but these areas have two problems; 1) the point spacing will be much greater than that shown in the green region, and 2) the angle between the scanner and the face is too steep. It is recommended to always use the appropriate scanner field of view, to reduce the point cloud size and eliminate non-optimum scanner angles relative to the rock face. When taking multiple scans of a single face, as discussed in the text associated with Figure 23, a non-optimum scanner angle relative to the face is acceptable if the purpose is capture data on structural features that are hidden from one direction. In this case, even though the angle between scanner and rock face may be small, the angle between scanner and a particular structural feature of interest will still be satisfactory.

Average point spacing in the point cloud is a very important parameter that should be optimized for a particular application. In general, point spacings of 2 cm or less are optimum for most of the geotechnical applications discussed in Chapter 4 (rock mass characterization, rockfall chute characterization, rockfall change detection). Point cloud spacings up to 5 cm are acceptable for the scanning of high slopes (such as Glenwood Canyon), but point cloud spacings greater than 5 cm are not recommended for any geotechnical applications. For non-geotechnical applications involving the generation of a 3D digital terrain model, point cloud spacings up to 10 cm could be acceptable. Figure 25 shows an example of a point spacing of about 1.5 cm, allowing features less than 0.3 meters to be delineated clearly.

Figure 25. Schematic. Point cloud example. Ideal point cloud with a point spacing of about 1.5 cm (yellow ruler showing 1.85 meters).

Taking Digital Images

High-resolution digital images should always accompany each point cloud. The digital images can be used stand-alone for rock mass characterization and rockfall applications, or registered with the point cloud using photo draping techniques. All new scanners have high-resolution cameras built in (or mounted on top), and digital images are part of the "data package" that is produced from these scanners. However, older scanners may only have a low-resolution camera or no camera at all, so it is important to take digital images separately in these cases. Even with the newer scanners, it is good practice to take digital images separately to document the scanning and the overall site conditions. Separate digital images can also be used to take close-up images of rock features of interest. In general, image scale and camera calibration is not required for digital images taken separately, since this information can be extracted from the associated point cloud.

Field Notes

In addition to the data from the scanner, surveying, and any digital images taken separately, field notes should be taken (either by hand or using a laptop or handheld) and the field notes file should be placed in the same computer folder as the other data. Field notes can include the following:

- Location of site (from GPS or map)
- Site geology
- Rock mass information that cannot be extracted from point cloud (rock weathering, discontinuity fill, Schmidt hammer readings, small scale roughness, etc.) In order to associate this information with scan-derived information, the GPS coordinates of each piece of data collected can be recorded.
- Miscellaneous information such as details of benchmarks or other data collection activities in the area.

DATA PROCESSING BEST PRACTICES

A basic description of data processing using point cloud processing and CADD software was described in Chapter 3. Here we describe some specific recommended procedures.

Data Management

Data processing with point cloud processing and CADD software produces a number of very large files. For instance, a point cloud file containing one million points will take up about 30 Mbytes as an ASCII file and about 10 Mbytes as a binary file. The file will become larger as digital images and other kinds of information (such as stereonets and text) are added to the file. As discussed in Chapter 2, one million points might represent the scanning of a 30 meters high by 40 meters wide portion of a slope. If a number of scans along a highway are stitched together, then the size of the file goes up accordingly. It is important to store more than just the "finished" DTM files (data files that have been triangulated, stitched, photo draped, edited, etc.) or just the extracted geotechnical data. At a minimum, the original files from the scanner should be stored, as well as the point clouds once they have been registered (preferably in the xyz format given in Chapter 2 so that the data can be easily opened in any point cloud processing program). Each scan or set of scans should have a dedicated folder that contains the raw scanner files, registered point clouds, field notes, digital images, CADD files, etc.

Point Cloud Stitching

Individual point clouds usually have 1 to 3 million points (for 2 cm point spacing, that's a square areal coverage of approximately 25-45 m (82-148 ft) on a side). A site may consist of ten or more point clouds (sequentially down the highway as in Figure 23, for example). The point clouds can either be viewed and processed separately, or they can be stitched together into a single combined point cloud. For extracting geotechnical data, it is not necessary to stitch the point clouds together, and in general it is not recommended to do so. This is because the combined point cloud may have 20 million points or more, and will be very difficult to visualize and rotate in point cloud software. Point cloud software such as Split FX does allow the individual unstitched point clouds to be in the same file, and to combine the fracture orientation data on a single stereonet without having to stitch the point clouds together. For other purposes, such as viewing and making 3D measurements, it may be advantageous to have a single stitched DTM. In this case, it is recommended that a triangulated surface is made and only the merged triangulated surface is used for combined 3D measurements.

Extracting Rock Mass Characterization Information

At the present time, the only point cloud processing package that has a number of built-in features for extracting rock mass characterization information is Split FX. Based on using the software for a number of years, some best practices are given in Appendix C.

THE COST OF A LiDAR SURVEY

As described in this chapter, LiDAR can be used to collect important field data for the analysis of highway slope stability, and there are safety, access and other advantages of doing so. In many instances, the collection of this data using LiDAR could represent a cost savings compared with traditional methods. For example, the following numbers are based on the collection of discontinuity orientation measurements along a 300 meter section of Highway 93 in Arizona:

<u>Traditional data collection and analyses:</u>

- Cell mapping, 350 joint orientation measurements, 2 people for 2 days
- Processing and making graphs of the data, 1 person for 1 day
- Total 5 man days (with overhead, assume $1000 per day)
- Share of equipment and software costs $250
- Total cost - about $5250 (mostly manpower)

<u>LiDAR with automated fracture analysis software</u>

- Field scanning (six scans) and digital imaging, 1 person for 1 day
- Data processing, 1 day
- Scanner rental, $1500
- Share of other field equipment (camera, etc.), $200
- Share of software costs, $800 (assumes 10 projects covers software cost)
- Total cost - $4500 (less than 50% manpower)

This would be considered a typical example where the hand-measurements are made at the base of the slope, and it indicates slight cost savings with LiDAR. If repelling down the slope was involved to collect the discontinuity orientation measurements, then additional cost savings would be expected with LiDAR.

THE ACCURACY OF LiDAR-GENERATED DATA

For extracting fracture information from point clouds, a key measure of accuracy is the error in the estimation of a fracture's strike and dip (or dip and dip direction). As discussed earlier in this chapter, Figure 5 compares fracture orientation data measured by hand with LiDAR generated fracture orientation data (white vs black stereonets, respectively). Overall, the location of major structural features appear to differ by less than 5 degrees between hand-measurements and LiDAR generated data. Of course, the hand-measured results themselves have errors that could be as large as 5 degrees. Therefore, the discussion in this section focuses on errors in LiDAR-generated results alone.

Errors in the LiDAR results are due to three primary sources:

1. Instrument accuracy and field settings
2. Procedures and accuracy of point cloud registration
3. Software and procedures used for processing point clouds

Each of these errors are briefly discussed below:

Instrument accuracy and field settings

For a typical scan of a rock face, often over 1000 laser points will intersect large fracture surfaces, while less than 50 points may intersect smaller surfaces. It is important to understand how the number of laser points intersecting a fracture surface and the error of the laser impact the accuracy in the estimation of the strike and dip of the plane. For this purpose a Monte-Carlo based computer model has been developed to determine the error in the calculation of strike and dip, based on a 3D laser scanner with given distance and position accuracies and a fracture plane with a given size and distance from the scanner. Details of the model are described in Kemeny et al. (2003). Here we consider two fracture sizes, both with a point density of about 2 cm (the recommended point spacing described in Chapter 5). In the first case 724 laser points intersect a 0.5 x 0.5 m^2 fracture, and in the second case 100 laser points intersect a 0.2 x 0.2 m^2 fracture. Scanner position and distance accuracies of ± 1.5 cm are assumed. This is a large error, and most 3D laser scanners are capable of scan accuracies less that this (see Table 1 and Appendix A).

For the case of 724 laser points hitting the 0.5 x 0.5 m^2 fracture plane, the Monte-Carlo model showed a mean variation in dip from the actual dip of 0.19 degrees with a standard deviation of 0.03, and a mean variation in dip direction of 0.1 degrees with a standard deviation of 0.015. For the case of 100 laser points hitting the 0.2 x 0.2 m^2 fracture plane, it shows a mean variation in dip of 0.93 degrees with a standard deviation of 0.3, and a mean variation in dip direction of 1.0 degrees with a standard deviation of 0.33. Overall these results are very promising and indicate that errors in the strike and dip less than one degree should be able to be attained even with small fracture surfaces, using almost any of the 3D laser scanners available today. It should be noted that the model does not consider some other sources of possible error, including atmospheric and temperature errors, or the errors discussed in the next two sections below.

Point cloud registration errors

This is an important source of error, and this error affects the calculated fracture orientations for all fractures regardless of their size. The error in the estimation of fracture orientation will depend on the registration method that is used. For instance, if registration is based on Brunton measurements (measurements of objects in the scene or of the scan direction itself), then the error will be ± 2 degrees or more. The most common method of scanner registration is to use 3 or more surveyed points (3D similarity transform). If three points are used, and assuming a surveying error of ± 1.5 cm, 3D similarity transformation results indicate a maximum deviation in strike and dip of about ± 0.2 degrees for a typical scan taken at a distance of 30 meters. This is very reasonable, and if more targets are used the errors should be even smaller. The errors associated with other methods of scanner registration are discussed in Reshetyuk (2006).

Software and procedures used for processing point clouds

Differences in how the point cloud is analyzed to determine fracture orientation results in large differences in the estimation of the strike and dip of a fracture surface. One method is to pick three points on a fracture and determine the orientation of the plane made by these three points. Because actual rock fracture surfaces are not flat planes, this technique will show large variations depending on the roughness of the surface and which three points are selected. A better method is to select all the points that make up the fracture and calculate the best-fit plane through those points. This method will also show variations because "selecting all the points that make up a fracture" is not a straightforward task, particularly near the edge of the fracture. If an automated routine is used to select the points that make up the fractures (such as the automated routine in Split FX), then changing the parameters in the routine will result in differences in the calculated best-fit orientations.

A COMPARISON OF LiDAR AND PHOTOGRAMMETRY

LiDAR and photogrammetry both produce a high-resolution 3D rendering of a scene of interest, but they are based on very different principles. As described in Chapter 2, a LiDAR point cloud is based on the reflections of pulses of laser light that are emitted from a scanner. Also, photo draping techniques can then be used to drape a high-resolution digital image onto a point cloud, as described earlier in this chapter. Many types of analyses can be conducted with the point cloud alone, including the determination of discontinuity orientation, roughness, length and spacing and block size. The draped photo can be used to determining discontinuity orientations for structures that have no exposed surfaces (such as a joint set in the scanner shadow zone) as well as assisting with the interpretation of geology, major structures (such as faults), and other things.

In photogrammetry, the 3D coordinates of a scene are determined from digital images taken of the same scene from different directions. In particular, information on the 3D coordinates is determined from the parallax, which is the change of angular position of two observations of a single object relative to each other. Details on photogrammetry can be found in Faugeras (1996) and many others. In the field, special stereo cameras can be used that have two lenses at a fixed distance and orientation relative to each other. Today it is more common to use a standard digital camera and take multiple images of a scene from arbitrary directions and positions. The multiple camera positions are then determined using a technique called bundle adjustment that involves "feature matching" in overlapping areas of the images. Photogrammetry software specifically designed for extracting geotechnical information from digital images include 3G (www.3gsm.at), Siro Vison (www.csiro.au), and Adam Technology (www.adamtech.com.au). Photogrammetry software ranges in price from $5,000 to over $50,000. A standard high-resolution camera can be used for field surveys, which can range in price from $500 to over $5000, depending on resolution and features.

A brief description of some of the differences between LiDAR and photogrammetry and the impact of these differences on highway slope stability analyses are given below.

1. LiDAR emits its own light, as opposed to photogrammetry, where either natural lighting is used or an external light source (such as flash lighting) is used. This can result in some differences. First of all, when scanning a slope that has vegetation, the LiDAR light can penetrate through small openings between the vegetation to provide information on the soil or rock underneath. Photogrammetry, on the other hand, will only give this information if there is enough natural light available behind the vegetation. Secondly, because photogrammetry relies on multiple images of the same scene, lighting differences can occur due to changes in light in different directions or changes in lighting between the time the multiple images are taken. Thirdly, when imaging an underground excavation, LiDAR has the advantage that no external light source is required (LiDAR scans can be conducted in the dark).

2. Photogrammetry needs to view a portion of a scene from a least two directions in order to determine the 3D coordinates of that portion of the scene. LiDAR can determine 3D coordinates from a single viewing angle. This can pose problems with photogrammetry when there are large variations in topography over small areas, such as in areas of dense vegetation or rock rubble.

3. Because images are taken from different angles with photogrammetry, the 3D DTMs from photogrammetry may not have as many areas of no data (scanner shadow zones) compared with a LiDAR scan from a single viewing direction. To address this problem, LiDAR scans can also be taken from different viewing angles, as discussed earlier in this chapter.

4. In the field, a LiDAR survey takes about the same amount of time as a photogrammetry survey. Because registration is required for both methods, much of the time in the field is taken up with issues involved with 3D registration (placing and surveying of targets, for example). The automatic output from a LiDAR scan is a point cloud, and no processing is required in producing a point cloud file. To produce 3D information from photogrammetry, on the other hand, many steps are required that require time and expertise with photogrammetry software. Photogrammetry also requires camera calibration, a pre-field step not required for LiDAR surveys. Once a 3D model is produced, the analysis of the model to extract geotechnical information is very similar between LiDAR and photogrammetry. Overall, if photo draping is not used in the LiDAR analysis, then the LiDAR survey and processing will take less manhours and require less software training than the equivalent photogrammetry survey. If photo draping

is used as part of the LiDAR analysis, this will increase the manhours and amount of software training for using LiDAR for highway rock slope stability.

5. The hardware are significantly less expensive for photogrammetry, consisting of only a high resolution digital camera and associated field equipment (tripod, etc.). The software costs for photogrammetry can be either cheaper or more expensive than LiDAR, depending on the specific software packages that are used with each method. The total cost of LiDAR survey can be cheaper or more expensive than an equivalent photogrammetry survey depending on many factors, including total manhours, software costs, and how the cost of the LiDAR equipment is calculated (it may be shared with other purposes or rented, for example).

6. The final accuracy of a 3D model, whether it comes from photogrammetry or LiDAR, depends on many factors, including the specific hardware and software used, the method and accuracy of scanner registration, and the specific field procedures. Based on published accuracies by scanner manufacturers (Appendix A) and photogrammetry software companies (see web sites listed above), it should be possible to get the equivalent accuracy from both methods.