ARMA 13- 663

Discontinuity mapping using Ground-Based LiDAR: Case study from an open pit mine

Tiruneh, H.W. and Stetler, L.D.

Department of Geology and Geological Engineering, South Dakota School of Mines and Technology, Rapid City, SD, USA

Oberling, Z.A., Morrison, D.R., Connolly, J.L., and Ryan, T.M.

Call and Nicholas, Inc., Tucson, AZ, USA

This paper was prepared for presentation at the 47th US Rock Mechanics / Geomechanics Symposium held in San Francisco, CA, USA, 23-26 June 2013.

ABSTRACT: Discontinuity data of rock masses are critical for the characterization, design, and analysis of rock fabrics as related to small- and large-scale slope stability. They present the most common challenges in the design of open pit mines as adverse rock fabric orientations may impart instabilities that have the potential to cause losses of life, infrastructure, and decrease in productivity. Therefore, accurate and precise characterizations of discontinuities are a crucial step in successfully designing stable slopes. Terrestrial LiDAR scanning coupled with high resolution images can be used for virtual mapping of discontunities. The benefits of implementing LiDAR as concerned with discontinuity mapping include ease of operation, improved safety, ability to collect data in inaccessible areas, short data acquisition time relative to manual data collection, and most importantly, pertinent rock mass data may be collected in much greater detail. A case study from an open pit mine was performed to evaluate if correlations exist among discontunity properties collected using different methods including (1) traditional cell mapping, (2) optical and acoustic borehole imaging (OBI and ABI, respectively) with sampled core and, (3) high resolution LiDAR scanning. The advantages and disadvantages of these techniques are discussed and recommendations based on the results are presented in this study.

1. INTRODUCTION

Geomechanical properties of discontinuities generally control the engineering behavior of rock masses. Discontinuities, defined as any mechanical break that has zero or relatively low tensile strength in a rock mass, are the most common weakness features in a rock mass. Discontinuity features include joints, fractures, fissures, foliations, weak bedding planes, and faults [1]. In geotechnical engineering projects, discontinuities are responsible for the most common challenges in the design of engineered structures in rocks. Therefore, engineered structures constructed in or on rock require proper site characterization of discontinuous rock masses [2].

Field characterization of discontinuity properties include collection of data for different parameters such as orientation, spacing, persistence, roughness, wall strength, aperture, infilling material, seepage, and number of joint sets. Typically, a large database is necessary to accurately represent site discontinuities. Data collected from these studies can later be used in numerical modeling, excavation and support design, and other engineering design works.

In open pit mines, bench slope stability studies consist of collecting data pertinent to intact and discontinuous rock masses. One of the most critical properties of discontinuities is their orientation in space relative to both each other and the bench slope face [3]. Similarly oriented planes of weakness generally cluster around one or more ‘discontinuity sets’ or ‘families’ [4]. The identification of these sets is an important step in the discontinuity characterization process.

In pit bench slopes, unfavorably oriented discontinuities can result in small to large scale failures that create dangerous working conditions. Therefore, an accurate representation of discontinuity set orientations can aid in slope stability prediction and analysis. Orientation data plotted on stereonets can be used to determine potential failure mechanisms. Figure 1 shows the kinematic analysis technique given by Hoek and Bray [5].

While collecting discontinuity data, it is necessary to obtain a large data set that accurately represents the sites geologic heterogeneities (e.g. lithology, rock fabric, alteration). Moreover, analysis performed statistically using these collected data can be fairly close to reality.

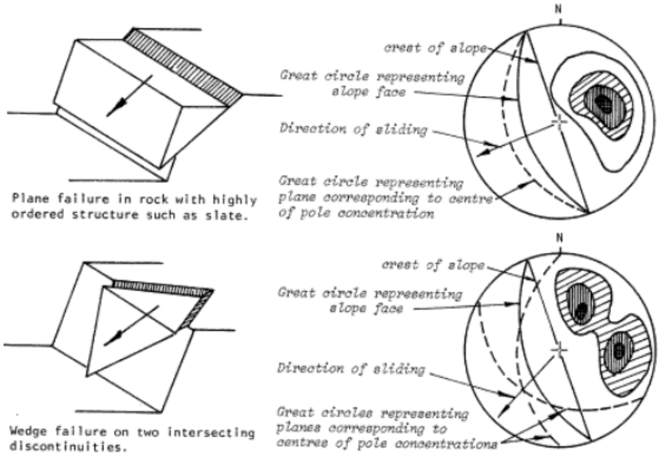

Fig. 1. Planar and wedge failure geometry (left) and their respective stereographic method of kinematic analysis (right) [5].

2. ROCK MASS CHARACTERIZATION TECHNIQUES AND THEIR DIFFICULTIES

According to ISRM [1], suggested methods for quantitative description of discontinuities include:

- Drillcore and drill hole description,
- Outcrop description and,
- Terrestrial photogrammetry (includes LiDAR Light Detection And Ranging).

Drillcore and drill holes provide an invaluable amount of information about the subsurface geological conditions. Data for the orientation, spacing, and roughness can be collected using this method. One important advantage of drill cores is that it is easier to take samples of discontinuities and the adjacent rock mass for deformability and strength tests [3]. Borehole geophysical logging techniques have also become a common method of characterizing rock masses and discontinuities at depth in drill holes. Televiewer borehole logging methods such as digital Optical Borehole Imaging (OBI) and digital Acoustic Borehole Imaging (ABI) are currently popular for mapping of discontinuities from drilled borehole walls. Televiewer borehole logging techniques used in this paper are described briefly in section 3.

Outcrop description consists of manual mapping methods, such as scanline and cell mapping. These techniques are the most common methods of characterizing a rock mass in an outcrop. Both scanline and cell mapping surveying techniques provide important discontinuity data that can later be analyzed statistically. These methods have been used for decades by geologists and field engineers. However, it is important to study the geomechanical behavior of the rock mass in an accurate and efficient way, as these data influence the final design of the engineering work. In practice, manual collection of rock mass data may suffer from difficulties and bias or errors due to the following reasons:

(i) Direct physical access to the rock face may not be possible at all times. Specifically while mapping high rock slopes and/or high underground excavation walls.

(ii) Working in dangerous areas creates a certain level of hazard to personnel collecting the data. Field manual data collection is typically performed in rock exposures where other activities are ongoing at the same time. For example, collecting data in busy road cuts or ongoing mining operations.

(iii) Working in unsupported areas can pose certain level of rock fall hazard to the personnel collecting the data. For example collecting data in underground openings immediately after blasting/excavation can create rock fall hazard.

(iv) Collected measurements are often subjective depending on experience and geological knowledge.

(v) Erroneous data can be introduced due to sampling methods, instrument error, and human bias.

(vi) Erroneous data are introduced due to estimating length rather than using a measurement tool such as tape.

(vii) Inability to manually measure effectively long trace lines (~ > 6m/ ~ > 20 ft).

(viii) Bias of scanline orientation which may lead to mapping of preferred discontinuities.

In addition, manual field data collection is typically time-consuming, labor intensive, and costly especially during collection of large discontinuity data sets [2].

Remote Sensing techniques such as Terrestrial Photogrammetry, LiDAR, and other methods have been developed over the last few decades that minimize errors traditionally introduced by manual field mapping. Furthermore, these methods provide supplemental rock fabric orientation data that enhance manual field mapping especially when collecting large discontinuity datasets [6]. Terrestrial digital photogrammetry and laser scanners are commonly used techniques for collecting accurate geometrical data automatically or semi-automatically. Advantages of using these techniques include:

- Ability to quickly analyze large areas and acquire large datasets.
- No direct contact with rock face.
- Ease of data acquisition.

- Ability to collect data in inaccessible areas.
- Short data acquisition time.
- Ability to collect accurate 3-D geometric representation of rock outcrop at higher resolution.
- Higher objectivity and precision in collected data [6].

This paper describes the correlations of the discontinuity orientation data that were collected using manual cell mapping with televiewer borehole logging data (using OBI and ABI) and that collected using Maptek's I-Site 8800 LiDAR scanner. Data collected using these methods will be compared and merits and demerits of each technique will be discussed and recommendations will be made based on the results and analysis.

3. TELEVIEWER BOREHOLE LOGGING: OPTICAL AND ACCOUSTIC BOREHOLE IMAGERY (OBI AND ABI)

Optical and acoustic borehole imaging (OBI and ABI, respectively) are televiewer surveying methods that utilize the geophysical principles of reflected light and sound waveforms to create a near-continuous down-hole image of the borehole wall. Televiewer imaging is becoming increasingly implemented in geotechnical, geological, and hydrogeological studies conducted by engineering firms and mining industries as a lower-cost alternative to more conventional core orienting techniques (i.e. Reflex ACT™ and clay-imprint methods). Both OBI and ABI are capable of imaging and quantifying geologic features including bedding planes, fractures, veins, and faults. However, the ability to confidently identify these features in image logs can be highly variable.

Optical borehole imaging is performed in dry or clear-fluid filled portions of the borehole by a probe equipped with a high resolution, high sensitivity CCD digital camera with matching Pentax optics that photographs the borehole wall. Mud-filled holes are imaged by a probe outfitted with a fixed transducer that emits ultrasonic pulses at specified intervals. It is possible to identify geologic features in the resulting image log as the intersection of an inclined planar feature with a cylindrical borehole creates an ellipse that when translated from 3-dimensions to 2-dimensions, results in a fixed-period sinusoid that is displayed from 0° to 360° (Fig. 2).

Acoustic image logs are illustrated as a false-gradation color scheme with low and high amplitude signatures depicted as cold and hot colors, respectively. Acoustic borehole imaging data acquisition is governed by differences in acoustic impedance (impedance mismatch) among the drilling fluid, adjacent rock formation, and discontinuities. A high impedance mismatch at the borehole/drilling fluid interface results in more energy being reflected rather than transmitted. Consequently, the transducer receives higher amplitude signatures. Lower impedance mismatches result in less reflected energy at the interface and the transducer receives lower amplitude signatures. The differences in impedance mismatches allow geologic features to be identified by acoustic televiewer surveying.

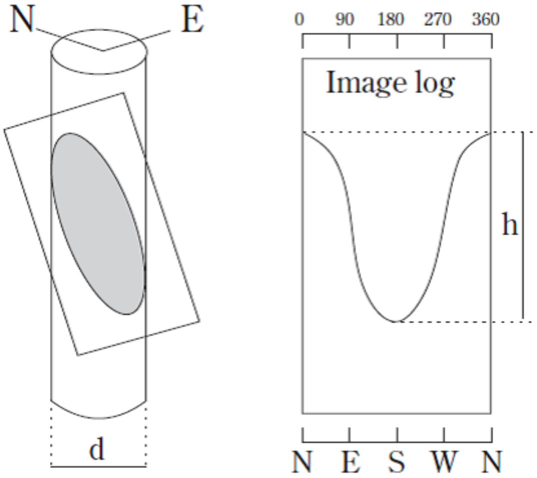

Fig. 2. Projection of a south dipping inclined planar feature intersecting a cylinder. The "unfolding" of the ellipse to 2D results in a fixed-period sinusoid. Note the point tangential to the sinusoids minimum equals the dip direction and dip angle = arctan (h/d) with h = height of the waveform and d = diameter of the cylinder (borehole) [7].

As with all televiewer imaging techniques, data collection can be extremely subjective and open for multiple interpretations. The main difficulty in interpreting rock fabric data collected from OBI and ABI logs for use in slope stability analyses is confidently identifying measurable open joints versus healed fractures and veins in varying core qualities. Features perpendicular to the core axis are also difficult to resolve in the image logs. The quality of OBI and ABI image logs are dependent on several factors including:

- Experience and training of the technician collecting raw data.
- Improper processing and optimization of raw data.
- Logging by personnel that are unfamiliar with the site's geology and project goals resulting in improper classification of geologic features.
- Discontinuity frequency, geometry, mineralogy, and aperture.
- Abundance of magnetically susceptible materials including Fe- and Ni-rich minerals and extent of drill hole casings.
- Rock color.
- Condition of drilled rock mass (RQD).
- Extent and style of rock alteration.
- Unmaintained or dirty probes.

- Borehole conditions including shape, rugosity, diameter, fluid turbidity and suspended dust (OBI) and wall coatings.

Low-quality image logs commonly result from poor borehole conditions and/or lack of training and operator experience. Many of the issues concerned with confidently identifying and classifying geologic features can be alleviated or completely eliminated by proper data optimization and logging by experienced personnel with the rock core present.

Optical borehole image logs are more sensitive to changes in rock and feature color (Fig. 3), fluid turbidity, suspended dust content, and fracture/vein frequency while ABI logs are impacted more by changes in borehole conditions and rock alteration; both are affected by discontinuity properties. Acoustic borehole imaging also provide two-way travel times allowing for open fractures to be identified with higher confidence as they typically show enlarged travel time signatures.

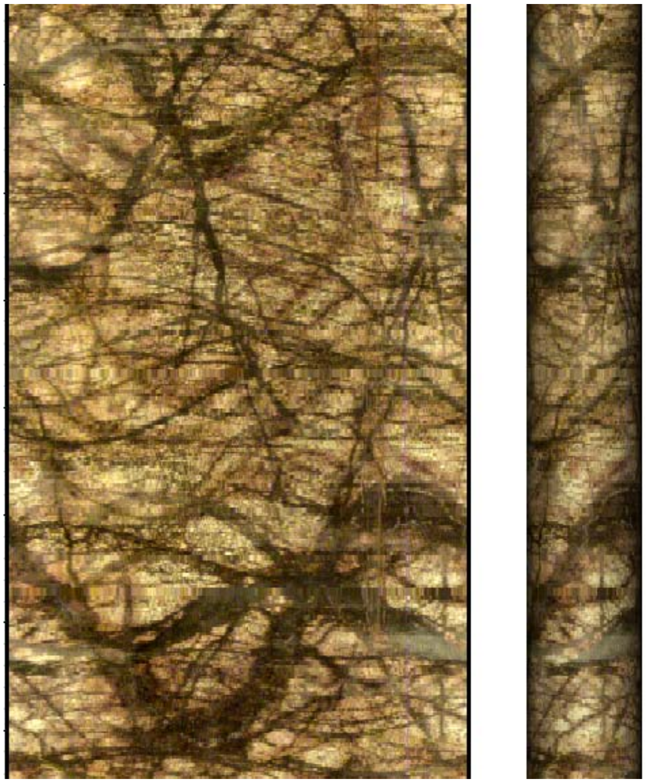

Fig. 3. Optical image log of Fe-oxidized granite porphyry. Note abundance of discontinuities that create difficulties in confidently differentiating between open joints and veins. Complex discontinuity geometries can offset pre-existing features forming partial sinusoids that are difficult to track diminishing confidence in orientation data.

For ABI, significant changes in any of the previously listed parameters may greatly diminish the quality of the image log reducing confidence in rock fabric data collected. For example, clay-filled fractures in a heavily sercitized and broken granite will have similar acoustic impedances. Therefore, relative to the drilling mud, the fractures and adjacent rock formation will have low impedance mismatches resulting in low-quality image logs with less prominent sinusoids (Fig. 4A). Conversely, a clay-filled fracture in relatively fresh granite will have higher impedance mismatches producing prominent and readily distinguishable sinusoids (Fig. 4B).

The reliability of OBI and ABI rock fabric data can be variable and are highly dependent on rock quality, data collection methods, and borehole conditions and should be treated with caution. It is prudent to validate any borehole fracture orientation data with other data sources (such as cell mapping, LiDAR scanning, and geologic structure maps) as a quality control check. If inconsistencies are observed, further investigation into potential causes may be warranted.

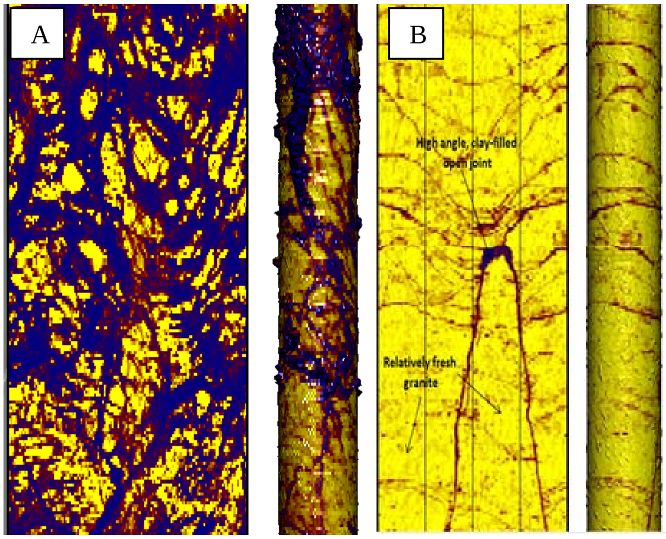

Fig. 4(A). Acoustic borehole image in a heavily sercitized and broken granite. Note low-quality and distortion of image log in figure. Continuous sinusoids are very difficult to trace with confidence due to high degrees of alteration and complex fracture geometries.

Fig. 4(B). Acoustic borehole image in relatively fresh granite with clay-filled open joints. Note the prominence of the clay-filled fractures (cold colored sinusoids) in the relatively unaltered granite (hot colored background). This is because the host granite has a higher impedance mismatch while the clay-filled fractures have a lower impedance mismatch relative to the drilling fluid.

4. LIDAR TECHNOLOGY

Laser scanning is utilized to obtain accurate geometrical information of an object using laser light. LiDAR is a type of laser scanner that uses the speed of light and very precise timing devices to calculate the distance between a laser emitter/receiver device and an object reflecting the beam. The primary output of a typical LiDAR scanner is a dense ‘point cloud’ of data consisting of up to millions of reflection points representing actual spatial points of the scanned object. Each datum point has 3-D (x, y, z) coordinates and a reflected laser intensity value.

Depending on the laser scanner type used, data collection rates range from 2,500 to 1,000,000 points per second [6]. These equipments are able to scan from distances up to 2km [8]. A high quality digital camera mounted on the LiDAR system acquires a digital image simultaneously with LiDAR data. The high-resolution color pictures that are taken while scanning can be 'texture draped' over the scan point cloud data so that each individual point contains additional R, G, B attributes attached to it. This output point cloud data can be triangulated to create a digital surface of the scanned object. This enables the user to calculate the area and volume of the scanned feature and moreover it serves as a permanent digital model record of the scanned object. Typically special software packages are required to register and filter the point cloud data and create a triangulated surface out of the point cloud data if desired.

LiDAR has broad applications including military, archeology, agriculture, traffic accident incident investigation, surveying, geology, engineering, and other areas. In the past few years, this technology has become popular in geology and engineering disciplines. In rock engineering practices it has been adopted in slope stability studies, rock fall monitoring, slope movement, and fracture mapping purposes. In open-pit mines, LiDAR scan data can provide accurate bench slope angles and catch bench width values that aid in assessing the effectiveness of the slope bench design as well as excavation and blasting practices.

For this study, LiDAR scanner was used to collect point cloud data and high resolution color photographic images. The type of scanner unit used to obtain the data was Maptek's I-Site 8800 laser scanner (Fig. 5) and the software package used for the data analyses was Maptek's I-Site Studio 4.0.

Fig. 5. I-Site 8800 LiDAR Scanner used for wall mapping [8].

Although LiDAR data collection is accurate, fast, and provides large amounts of data, there are limitations and biases associated with the data collection, handling, and interpretation process. Limitations of terrestrial laser scanners include:

- Discontinuity surfaces that are striking parallel to sub parallel and/or that are dipping at the same angle as the line-of-sight of the LiDAR scanner have low laser reflections from this joint set, thus they will be shadowed [9][10].
- LiDAR cannot replace on-site field mapping techniques. Experienced personnel are always needed to qualitatively/quantitatively describe the rock mass strength, water condition, weathering condition, infilling of joints, and aperture. Moreover, the structural network of the discontinuities needs to be interpreted at the site. Therefore manual field mapping is needed in combination with LiDAR scanning [9].
- Shorter trace length truncation can occur especially when creating TIN surfaces from point data because it rounds or smoothes the edges of these surfaces to fit them with the adjacent point data [10].

5. CASE STUDY FROM AN OPEN PIT MINE

In this paper a case study was conducted to assess the correlation of the discontinuity data that were collected using traditional cell mapping with borehole televiewer (OBI and ABI) and that collected using Maptek's I-Site 8800 LiDAR scanner. The case study was carried out in excavated bench wall slopes of a large open pit mine. Rock fabric orientation data were collected from high walls composed of sedimentary and intrusive rocks including limestone, quartzite, granite, and granite porphyry.

The cell mapping procedure consisted of dividing the bench faces into windows of equal length. These individual windows are referred to as cells. For each cell, the dimensions were that of the height of the bench face height. For this study the selected pit wall area consisted of approximately 30 m (100 ft) and 15 m (50 ft) high bench faces. Therefore the mapping cell sizes used were 30 m x 30 m and 15 m x 15 m windows. Bench faces that are not covered with blasted material or by overbank were selected for mapping. Two adjacent bench levels faces were used to map the discontinuities and a total of 50 cells were mapped. A total of 218 discontinuity data measurements were taken including properties such as discontinuity type, dip and dip direction, spacing between similar sets, maximum discontinuity length, aperture, type of infilling, large scale roughness and terminations. In addition, information for the cell number, width and height, rock type, bench face strike and dip, distance over which the number of fractures in a discontinuity set, and water condition was recorded. A stereonet plot of the identified discontinuities is shown in Figure 6.

Geotechnical holes that were drilled near the mapped bench face were also used to study the subsurface geological condition. OBI and ABI televiewer data coupled with core samples were used to identify and characterize the discontinuities from the subsurface samples. WellCAD reader software was utilized for image orientation, optimization, and for identifying discontinuities. Two HQ3 near-vertical drill holes located east to south-east from the mapped bench faces were imaged with OBI and ABI providing 560 discontinuity orientation of faults, contacts, and joints. The combined drill hole depth equals approximately 196 m (643 ft). A combined stereonet plot showing the discontinuities mapped from the televiewer image logs is shown in Figure 7.

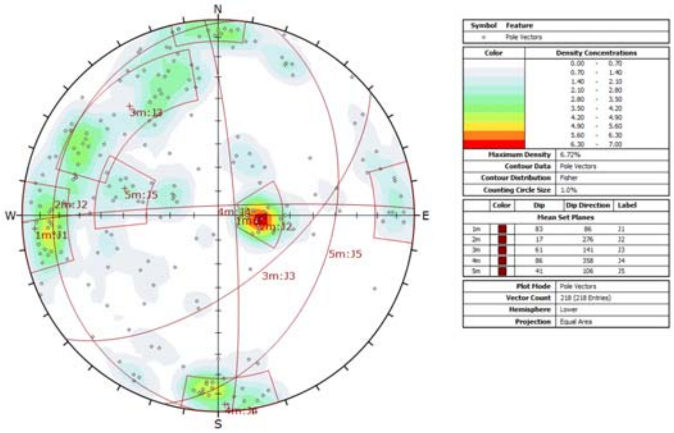

Fig. 6. Stereonet plot showing identified sets from cell mapping plotted in Rocscience Dips 6.0 software.

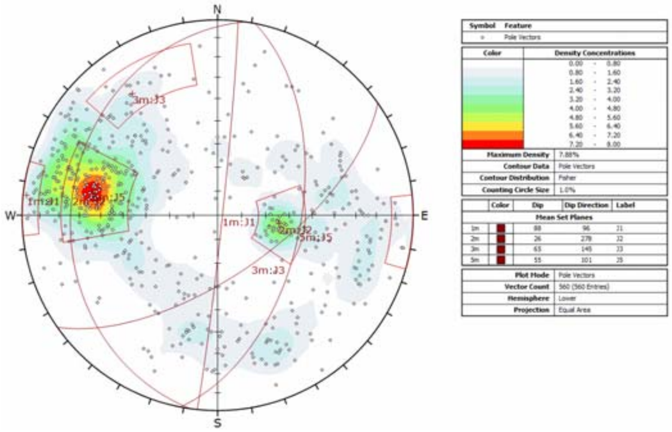

Fig. 7. Stereonet plot showing identified sets from Televiewer data (OBI and ABI) plotted in Rocscience Dips 6.0 software.

Bench faces that were mapped manually have been scanned using Maptek's I-Site 8800 LiDAR scanner from multiple locations. A high resolution photographic image (70 megapixels) was also taken simultaneously while scanning the bench slope faces. Before scanning started, the scanner took a photographic image of the entire 360^0 field of view, and the area of interest was selected on the tablet PC that was connected to the scanner. A high density level setting was selected to scan the bench face. The entire time that was spent to perform the two scan setups locations was about 1 hour and this includes the driving time to the two setup locations.

Once the scanning was completed, the raw point cloud data were transferred and filtered using Maptek's I-Site Studio 4.0 software package. Data processing steps that were performed before the raw data was used for geotechnical data collection include registration, rotation and filtering (dust and other objects that obstructed the scanned area were filtered). A triangulated TIN surface was also created and the high resolution photographic image was draped over it to create a detailed 3D model of the bench faces. Figure 8 shows point cloud data with a photographic image of portion of the bench face that was scanned.

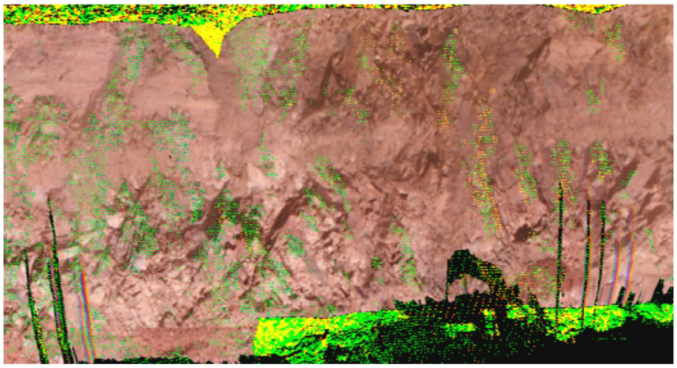

Fig. 8. Point cloud data of the bench face with photographic image draped on it.

The 'Geotechnical Menu' in I-Site Studio was used for this study to digitize and analyze the different discontinuity properties. In this new I-Site Studio release, users can select a planar feature and the software can automatically identify discontinuity features that have similar orientation (users can define orientation range within certain angle measurement) to the one selected (Fig. 9). This automated selection can be further narrowed to select planar features having a user defined minimum area. This method was used for this research but data result was later refined and inspected as there was a noise in the data result. Some of the fitted surfaces that were created automatically were representing the same discontinuity feature but were created more than once since the discontinuity surface was very large and there was a minor change in the orientation. Moreover, since the automated technique selects any planar feature that have similar orientation regardless of the aerial size, very small planar features that may not have an influence on the overall stability of the rock face were also automatically selected. Thus the results from this automated method must be inspected and edited before simply accepting the data result.

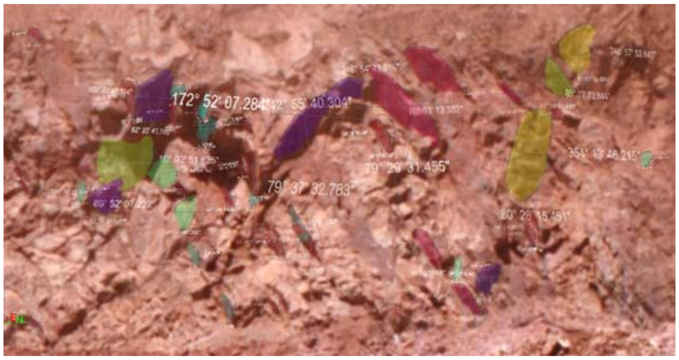

Fig. 9. Fitted planes for the observed discontinuity surfaces.

The identified discontinuity orientation can be plotted and viewed in a stereonet in the Geotechnical menu. This will allow the user to identify and delineate discontinuity sets. The orientation data can be directly exported to other softwares\ packages (using different formats such as excel, text etc) such as Rocscience's Dips to further analyze the data. For this study a total of 851 discontinuity features were identified and digitized. A stereonet plot for the identified sets is shown in Figure 10.

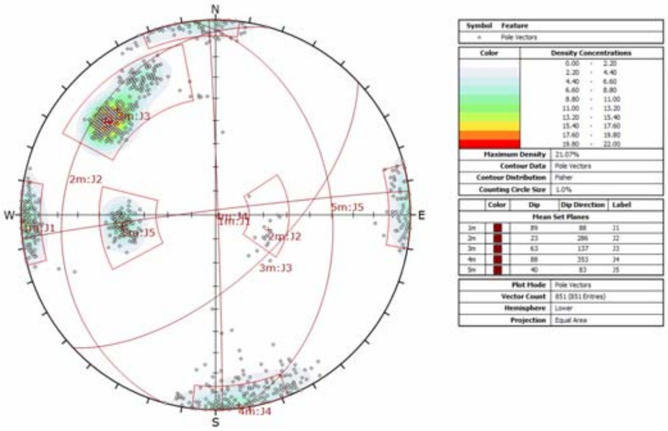

Fig. 10. Stereonet plot showing identified sets collected from LiDAR data plotted in Rocscience Dips 6.0 software.

The stereographic plot of discontinuities mapped using LiDAR and cell mapping suggests a total of five major distinct discontinuity sets. The total number of discontinuities that was sampled and analyzed in each technique is shown as bar graph in Figure 11. This figure shows that the data collected using the LiDAR technique resulted in a large amount of orientation data compared to the other techniques.

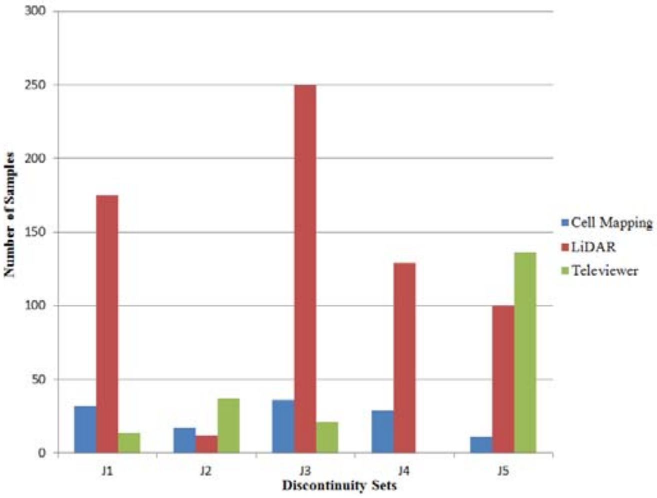

Fig. 11. Bar graph showing the number of discontinuities identified in each set from each method used.

A comparison summary of the discontinuity orientation using the different methods is shown in Table 1.

Table 1. Comparison of dip direction and dip amount data that was collected using cell mapping, LiDAR and televiewer techniques.

Joint Sets and Mean Orientation		Mapping Method Used		
		Cell Mapped	LiDAR	OBI and ABI
J1	Dip Direction	86	88	96
	Dip Amount	83	89	88
J2	Dip Direction	276	286	278
	Dip Amount	17	23	26
J3	Dip Direction	140	137	145
	Dip Amount	61	63	65
J4	Dip Direction	358	353	Not Identified
	Dip Amount	86	88	
J5	Dip Direction	106	83	101
	Dip Amount	41	40	55

6. FINDINGS AND DISCUSSIONS

In this study, the plots of discontinuity orientation data suggested a total of five major discontinuity sets. There are three discontinuity sets, J1, J2, and J4 that are nearly orthogonal to each other. Two of these sets, J1 and J4 were easily identified and mapped/digitized from LiDAR scan and cell mapping data. Large amounts of data were collected for these sets using the LiDAR scanner. This is mainly because the sets were well exposed to the LiDAR line of sight and were easily identified and digitized on the I-Site software. Analysis of the collected data using stereonet plot showed that there is a good correlation between the data collected for these sets using cell and LiDAR mapping techniques. Joint sets J1 and J2 were identified with the televiewer data but J4 was not identified. This could possibly be from the low RQD value of the recovered cores and the low impedance on the televiewer data which makes it difficult to pick the structures. Moreover it could be possible that the drill holes are near vertical thus chances of intersecting near parallel structures is generally diminished.

For discontinuity set J2, there is a good correlation among the data collected using all the methods. The reduced amount of data that was obtained using LiDAR for J2 set is because this set was oriented nearly parallel with LiDAR line of sight and was dipping at shallower angle into the bench face. Therefore there were only few laser reflections from this joint set compared to the other sets. Scanning of the bench face from different angle and/or elevation may result in receiving laser reflections from the planes of J2 sets.

Joint sets J3 and J5 were also identified and mapped using all the techniques and there appears to be a good to satisfactory correlation between the collected data respectively.

The data collected using the LiDAR scanner can be further analyzed for studying other important discontinuity geometrical properties such as spacing, roughness, persistence (in terms of trace length), bridge length (length of an intact rock between adjacent discontinuities), and block size [6][9]. Moreover other applications of the LiDAR unit in mining operations include stock pile volume calculations and volume changes, pit slope wall monitoring system, creating contour lines for surveying, for accurate volume calculations of overburden removals, pit geometry, identification of toe and crest of benches and evaluation of pit designs and others.

7. SUMMARY AND CONCLUSIONS

Standard manual mapping methods such as scanline and cell mapping are common techniques used to characterize rock masses. These mapping methods may be time consuming and access to the area to be mapped may not always be possible especially in active mine operations. Moreover, areas such as large bench slopes can pose rock fall hazard to the personnel collecting the data. Advances in LiDAR technology have allowed geologists and engineers to increase their productivity in field mapping tremendously. The advantage of using LiDAR technology over traditional field mapping is that the collected data are accurate, can provide a large discontinuity dataset, and it can cover larger areas. Moreover, the time spent to collect the rock mass information is relatively low.

This paper outlines the work performed for the evaluation of discontinuity characterization data collected from a large open pit bench slope faces using traditional cell mapping, televiewer borehole logging, and I-Site 8800 LiDAR scanner. A stereographic plot of the measured discontinuity orientation data from all the techniques used suggests a good correlation between the different data collection methods. This was also shown statistically using the collected orientation data. The results from this study also showed that a LiDAR system can be used to help extract large and accurate discontinuity datasets and to obtain a quick assessment of structural features. Although not discussed in this paper, other discontinuity geometrical features such as trace length, roughness, bridge length, block size, and spacing can be extracted from a LiDAR data.

Bias/limitations related to the use of LiDAR systems include orientation and truncation of discontinuity sets; these issues can be avoided by careful planning of the scanning operation including scanning the same face using multiple perspectives. The automated orientation result from the software shall be carefully inspected and edited to avoid including erroneous data. In conclusion, LiDAR systems can be effectively used to supplement cell mapping data to create a more robust discontinuity database. Rock fabric orientation data collected using LiDAR should be used in concert with other methods as a means of quality control; it should not be used as the sole source of discontinuity orientation data in slope stability analyses.

ACKNOWLEDGEMENTS

The authors would like to thank Clayton Fritz from Maptek's Denver office for assisting us in the initial processing of the LiDAR data as well as Bob Crowder and Jason Oberling for invaluable reviews of the OBI and ABI content.

REFERENCES

1. ISRM. 1978(b). Suggested methods for the quantitative description of discontinuities in rock masses. *Int. Journal of Rock Mechanics Mining Science and Geomechanics Abstr.* (15): 319-368.
2. Slob, S. 2010. Automated rock mass characterization using 3-D terrestrial laser scanning. PhD thesis. *Delft University of Technology*, Delft, Netherlands.
3. Priest, S.D. 1993. *Discontinuity Analysis for Rock Engineering*. 1st ed. London: Chapman and Hall.
4. Goodman, R.E. 1989. *Introduction to Rock Mechanics*. 2nd ed. New York: John Wiley and Sons.
5. Hoek, E.V. and Bray, J. 1972. *Rock Slope Engineering*. Revised 3rd ed. London: Institution of Mining and Metallurgy.
6. Kemeny, J., Turner, K. and Norton, B. 2006. LiDAR for Rock mass characterization: Hardware, Software, Accuracy and Best-Practices. In *Laser and Photogrammetric Methods for Rock Face Characterization, Golden, 17-18 June 2006*, eds. Tonon, F. and Kottenstette, J., ARMA Conference.

7. Gaillot, P., Brewer, T., Pezard, P. and En-Chao Yeh. 2007. Borehole Imaging Tools – Principles and Applications. *Deep Earth Sampling and Monitoring*. (1): 1-4.
8. Maptek 8800 I-Site Laser Scanner www.maptek.com
9. Strouth, A. and Eberhardt, E. 2006. The use of LiDAR to overcome rock slope hazard data collection challenges at Afternoon Creek, Washington. In *Laser and Photogrammetric Methods for Rock Face Characterization, Golden, 17-18 June 2006*, eds. Tonon, F. and Kottenstette, J., ARMA Conference.
10. Levy, M.E. and Visca, P.J. 2009. Statistical Characterization of Rock Structure using LiDAR. In *43rd US Rock Mechanics Symposium and US-Canada Rock Mechanics Symposium, Asheville, 28 June – 1 July*.