Applications of point cloud technology in geomechanical characterization, analysis and predictive modeling

by J. Lyons-Baral and J. Kemeny

Point cloud technology is now an indispensable tool in geological and geotechnical data collection, interpretation and analysis. Openpit and underground mines of all sizes are regularly collecting point cloud data as laser scanning (LiDAR) and photogrammetry surveying devices have become affordable and the workflows fast and efficient. Past challenges of large data processing and manipulation are gone with recent technological advancements in computer hardware and software. These innovations reduce file sizes, ease rendering requirements and allow for the implementation of real-time 3D viewers and surface meshing tools. With its ability to remotely and safely, rapidly and accurately extract large quantities of georeferenced and 3D-oriented data, point cloud technology provides numerous applications to the geomechanical field. The list of uses is continuously growing. This article specifically focuses on digital outcrop modeling and digital terrain engineering.

Point clouds. The high-resolution and increasing availability of point cloud technology is rapidly improving openpit and underground mines' investigation, interpretation and characterization of site geology and rock mass properties (Kemeny et al., 2015; Lyons-Baral, 2012). LiDAR and photogrammetry are common remote sensing methods employed to measure the coordinates of surfaces in three dimensions (3D), providing the X, Y and Z locations and typically the reflective intensity and/or the visible three-band color of each point (Fig. 1).

LiDAR uses either a time-of-flight or phase-shift measurement of a laser beam reflected off targeted surfaces and received back into the device.

Photogrammetry generates point clouds by merging multiple overlapping photographs and uses stereographic plotting to define the locations of object points in 3D space. These

Figure 1

3D color point cloud and resulting mesh surface showing a slope failure with crest scarp and toe bulge.

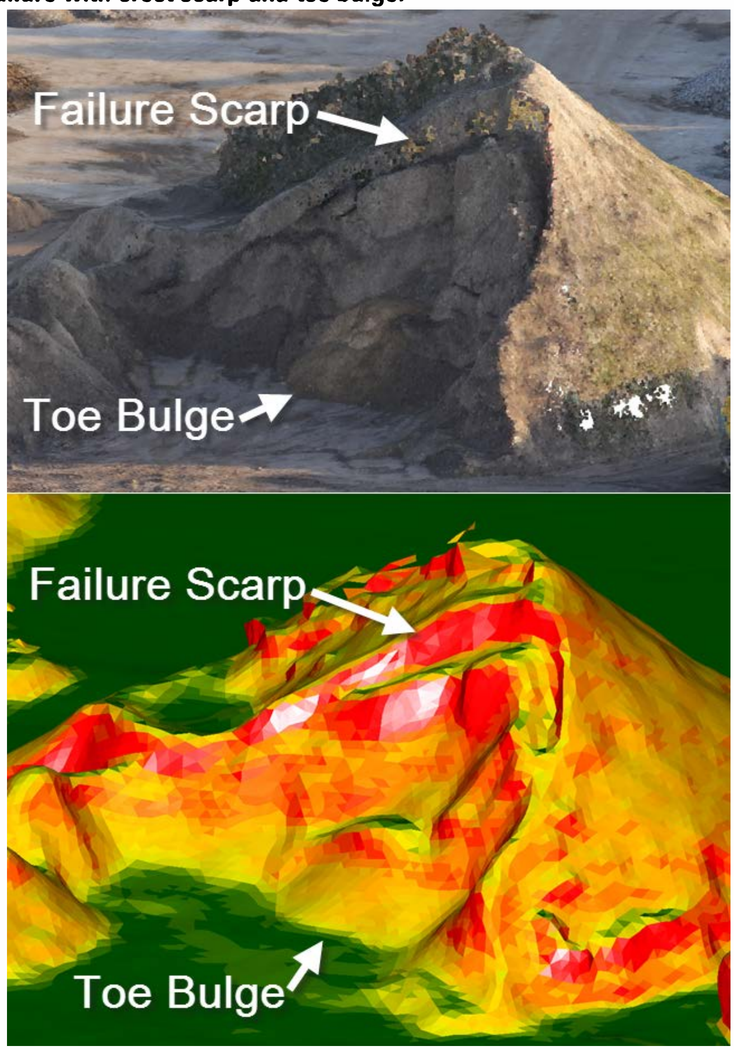

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Figure 2

Leica Pegasus: Backpack (Hexagon Geosystems, 2015).

methods can be deployed from airplanes, unpiloted aerial systems (UAS or drones), tripods, land vehicles and even in a mobile backpack shown in Fig. 2. RADAR, Total Station-Prism and other remote sensing systems also offer very precise "point clouds," but this article does not address these due to their higher cost and lower versatility and mobility.

Technology. In the past few years point cloud acquisition device prices have dropped significantly, devices have become lighter, smaller and easier to operate and processing and utilizing the data has also become faster and easier. Device size improvements include mobile backpacks (Fig. 2) and handheld mobile LiDAR (CISRO, 2014), allowing mobile scanning in tight spaces both above and below ground or inside and outside of man-made structures. Airborne data acquisition options have expanded dramatically with the spread of UAS technology as seen in Fig. 3 (Hexagon Geosystems, 2015). Once UAS usage regulations are sorted out, these versatile machines will be widespread, offering high resolution coordinate scans, imagery and other remote sensing. While backpacks and handhelds allow access to tight quarters, UAS permit rapid data capture from narrow to broad areas with multiple perspectives reducing data "shadows."

The range of scanning has increased to at least 6 km (3.7 miles) for terrestrial (RIEGEL, 2014) and 5 km (3.1 miles) altitude for airborne machines (Hexagon Geosystems, 2015). The sampling rate for fuller resolution scans has increased dramatically to at least one million points per second (Hexagon Geosystems, 2015). At the same time data processing time and difficulty have decreased with more automatic software options for point cloud registration, photogrammetry, editing and geometry extraction, level of detail rendering capabilities and readily available powerful computers (Hexagon Geosystems, 2015; Hexagon Mining, 2015, 3DReshaper, 2014; Split Engineering, 2014).

The continuous coverage and precise locations and geometries of geology and rock mass provided by point clouds are unrivaled both on the surface and in dark subterranean environments. Some significant benefits of this method of investigation and data collection are: accurate geomorphic, stratigraphic, structural and geotechnical mapping in-out-of reach, dangerous areas or dark areas. Point cloud technology is rapidly becoming an indispensable tool in geological and geotechnical data collection, interpretation and analysis. Openpit and underground mines should now all be collecting and utilizing point cloud data as previous roadblocks are being thrown aside due to ongoing technological advancements in computer hardware and software.

Figure 3

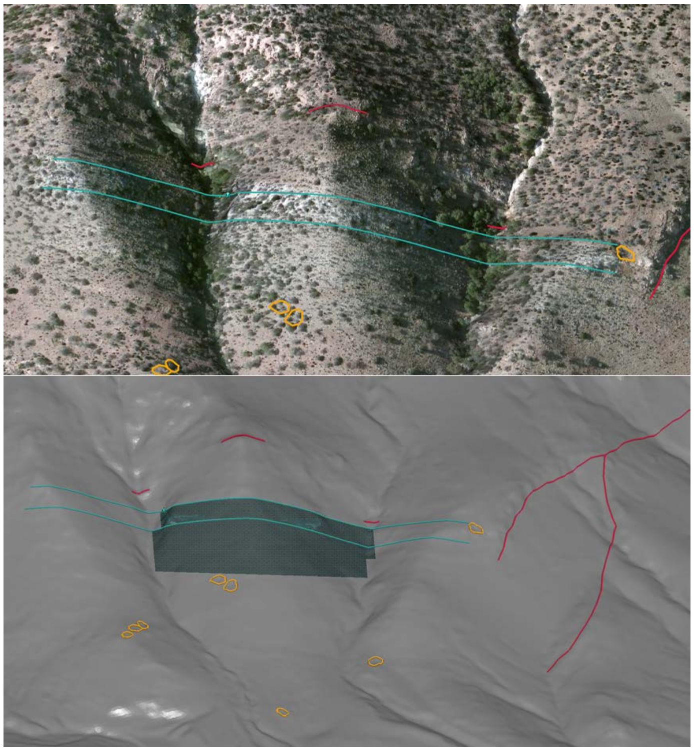
Aibotix UAS Aibot X6 Hexacopter (Hexagon Geosystems, 2015).

Digital outcrop modelling

A digital outcrop model (DOM) is a digital 3D representation of an outcropping (exposed) geologic surface. These surfaces, combined with imagery and other remote sensing data and mapping data, allow for accurate geologic mapping and interpretation, rock mass characterization and 3D surface to subsurface data linking. Surface outcrop point

Figure 4

Geologic interpretation of karst terrain showing sinkholes (orange), faults (red), bedding lineations and planes (sea green) (Lyons-Baral, 2014).



cloud mapping and analysis are frequently being conducted by those in geotechnical engineering, geomorphology and petroleum geology. Both qualitative and quantitative analyses are important aspects of outcrop modeling.

Geologic interpretation. Geoscientists and geological engineers are challenged to deduce often deep and expansive interpretations of the earth's geology. Their job is to find meaningful connections and correlations between initially independent surface and underground data in order to gain a more accurate understanding of a site's earth materials, structures and processes. This interpreted model then becomes the basis for further exploration, predictive modeling and engineering designs. Point cloud data have become an indispensable part of this workflow. Integration of high-resolution color imagery with 3D models is extremely useful for geologic interpretation not only because it can convey information about geometry, but also non-geometric attributes such as the distribution of alteration or weathering, locations of seeps and variations in rock type (Haneberg et al., 2006).

Geomorphologists and engineering geologists very commonly use point cloud-based bare earth digital elevation models (DEM) to identify sinkholes and karst features, landslide scarps, tension cracks, hummocks and levees (De Waele et al., 2011). Alexander et al. (2013) note that where LiDAR DEMs have been used in Minnesota the number of mapped sinkholes has roughly doubled. Lyons-Baral (2014) found LiDAR-based ground and cave point clouds useful for locating sinkholes, strata, faults, fractures and water sources (Figs. 4 and 5). Because the data were in georeferenced 3D space, not only was location determined, but accurate orientations were also easy to extract. 3D geomodeling allowed for analysis of spatially correlated attributes for any data in the geologic model.

Petroleum geologists have been increasing their use of outcrop point cloud scanning to better model the structural and stratigraphic geology of hydrocarbon reservoirs (Fig. 6). Hodgetts (2013) lists 24 peer reviewed papers of digital outcrop analogue studies. Attributes generated from the data, manual interpretation and automated approaches have been used to extrapolate and interpolate the reservoir characterization needed. Outcrops provide geometric data, such as width, thickness, position and orientation. They also provide qualitative data, which are conceptual models and depositional systems based on outcrop interpretation. This data can be used to bridge the gap between well bore and seismic data. In particular they focus on digital extrapolation, interpolation and interpretation of the fractures and strata into 3D modeling space.

Rock mass characterization. The determination of the engineering properties of a particular site's geologic material is called rock mass characterization. This method looks at the rock formation as a singular larger mass of material that has internal properties defining its strength and elasticity. Instead of only looking at each intact rock piece to understand the engineering properties of the mass, the pieces are considered part of the whole, with the fractures and voids considered as the porosity in the material. It is important to see the rock mass this way, because engineered earth structures will interact with the earth in this manner. Groupings, divisions and domains are created where necessary to accurately represent differences in anticipated rock mass behavior.

Kemeny et al. (2015) and Kemeny and Kim (2009) demonstrate the use of point clouds for road cut and outcrop slope stability analysis and discontinuum modeling. They found that rock mass fracture characterization can be conducted remotely using point clouds, keeping field workers out of dangerous areas while collecting significantly more fracture measurements than hand or cell mapping methods. Measurements

Figure 5

Cave mesh surface from LiDAR showing bedding and joints (Lyons-Baral, 2014).

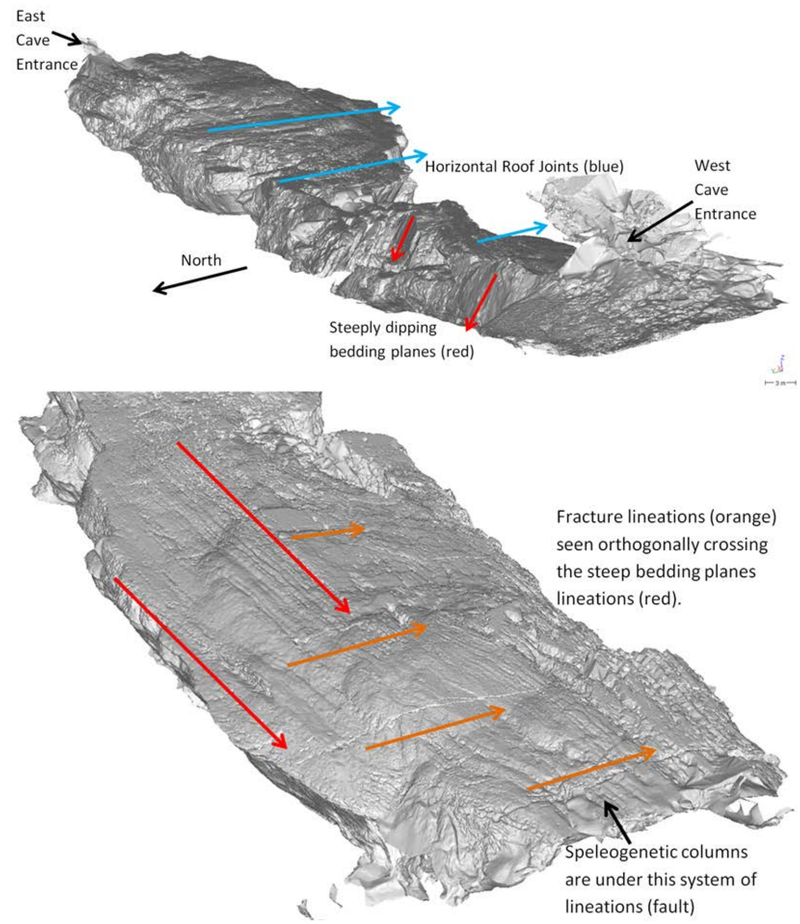


Figure 6

Surface outcrop LiDAR interpretation and subsurface modeling workflow (Enge et al., 2014).

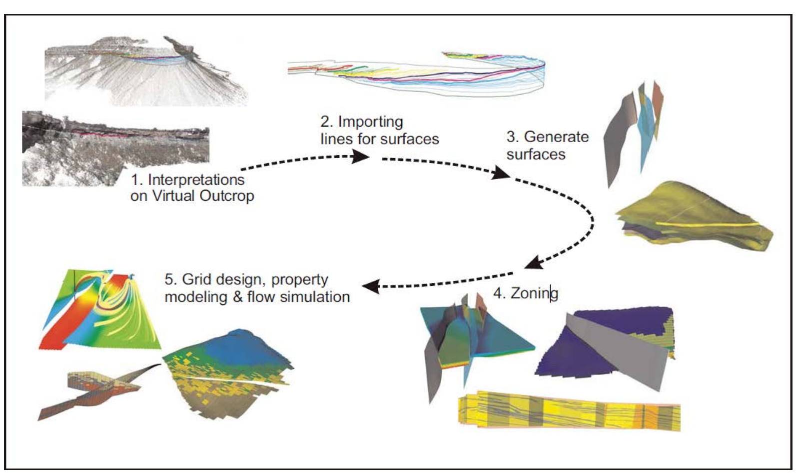
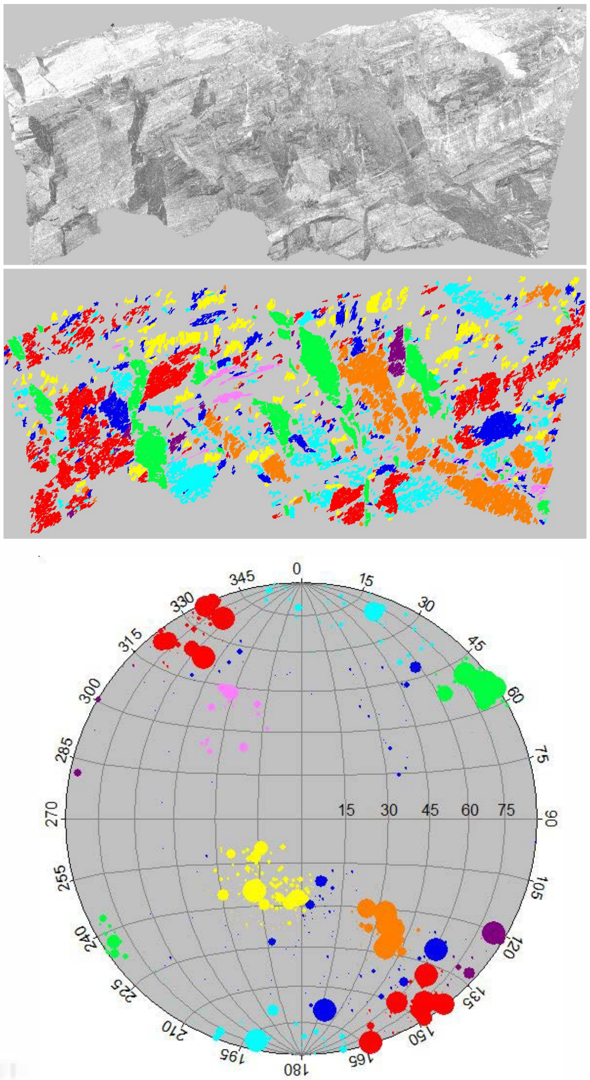


Figure 7

Color point cloud with automatically delineated structural fracture polygons and stereonet of fractures and joint sets (Kemeny et al., 2015).



obtained via LiDAR were fracture orientation, roughness, persistence, spacing and rock quality designation (RQD) (measures the percentage of intact rock that is greater than 10 centimeters per 1 meter length (Figs. 7 and 8). The fracture orientation data was then plotted and analyzed statistically and kinematically using stereonets to determine which modes of failure are geometrically possible and statistically probable (Fig. 16). Then 3D modeling took the LiDAR results one step further to look at slope factors of safety and probabilities of failure.

Surface to subsurface linkages. More and more, scientists and engineers are discovering methods to improve interpretation and characterization by combining surface point clouds with subsurface point clouds or geophysical surveys. The coupled use of ground and underground data provides more accurate 3D models of bedding, faults, conduits, sinkholes, thicknesses and curvatures. The significance of this is the ability to visualize a subsurface feature that is also clearly expressed on the surface or vice versa. Surface to subsurface connectivity may mean that a fault is relatively active; it may mean that a fracture set is very persistent and prone to large failures; it might indicate that a surface depression is more likely to become a sinkhole or may show that surface water can quickly penetrate to the subsurface increasing risks from pore water pressure.

Enge et al. (2014) demonstrate methods for taking outcrop geometric data and extracting it into 3D subsurface reservoir models. DOMs were merged with geophysical and borehole data to significantly improve reservoir modeling. Hubbard et al. (2012) demonstrate the use of combining surface LiDAR with subsurface geophysics. The project was conducted to test the benefits of combined surface LiDAR and subsurface geophysical characterization. This method directly ties fine surface details accurately to subsurface features identified in the geophysical surveys. The geophysical methods combined with LiDAR were GPR, electrical resistance tomography (ERT) and electromagnetic (EM). They found a strong correlation between the LiDAR zonation and the geophysical zonation, leading them to infer that the subsurface characteristics in the active and permafrost layers had a direct connection to the surface morphology.

Griffith et al. (2014) found that the often ignored valley topographies above underground coal mines have a significant impact on the regional stress field. Using 3D boundary element modeling with the actual LiDAR-based DEM over the mine, they computed the maximum compressive stresses can vary as much as 30 percent compared to analysis using flat topography and only regional stresses considered. In some regions of the mine, the stress differences were enough to reveal significant instability that had gone unmodeled previously but corresponded well to known areas of rock control issues. Visible geometrical linkages can be made where both surface and subsurface point clouds are available, as Lyons-Baral (2014) showed at Coronado Cave, AZ (Fig. 9). He was able to demonstrate surface topographic inflection point connected directly to cavern structural features when extruded to the surface.

Predictive modeling. 2D and 3D predictive modeling analyses are natural extensions of high resolution point cloud terrain modeling. Stress, strain and deformation are significantly controlled by the geometry of the materials. Precise thicknesses and angular stress concentrations or relaxations have a huge impact on the stability of rock masses. And the same geometric importance applies to rockfall simulation modeling – precise angular protrusions and benches are one of the dominant factors in trajectories and run-out of falling rocks. Kemeny et al. (2015) found that point clouds provide significant detail in vertical cross sections that can be used to look for overhanging rock slabs or for protrusions to determine rockfall trajectories (Fig. 10).

Lyons-Baral (2014) found that high-resolution 2D cave section polygons showed significant increases in predicted failing joints and rock mass elements in 2D stress modeling. High-resolution geometries showed between 25 and 55 percent increases in yielded (failed) joints (Fig. 11). And for yielded rock mass elements, low-resolution data were showing no failures while high-resolution showed areas around the cave walls where failure is likely to occur. The point cloud-based cave geometries indicated more hazardous conditions and matched the rock fall patterns (fallen blocks and talus) in the cave very well, while the low-resolution polygons did not reveal the full extent of potential hazards.

Digital terrain engineering

Digital terrain engineering (DTE) is the design, validation and monitoring of engineered earth structures such as slopes and tunnels. DTE relies on the use of digital terrain models (DTM) or DEMs to create accurate and optimally safe designs, compare designs versus as-builds, and monitor the deformation of the structures throughout their lives.

Design versus as-built. It is impossible to engineer earth structures to very precise specifications compared to steel and concrete. Yet safety and financial optimization rely on engineering designs that strive to find that perfect balance between reducing risk and maximizing profit. Therefore, it is critical to inspect the as-built slopes and tunnels to ensure they are within the given tolerance to be safe yet not wasteful. And this economic optimization also lends itself to more sustainable mining, reducing the amount of unnecessary waste removed.

When working with earth masses, blasting and excavating tools are used to clear away and shape rock and soil. But due to the heterogeneous nature of the materials and the large scale building methods, the resulting shapes are quite irregular. This is expected and is allowable within a tolerance. Point cloud technology provides a fast, safe and easy way to survey as-built surfaces and tunnels to compare

Figure 8

Measurement of joint spacing for a single fracture set (Kemeny et al., 2015).

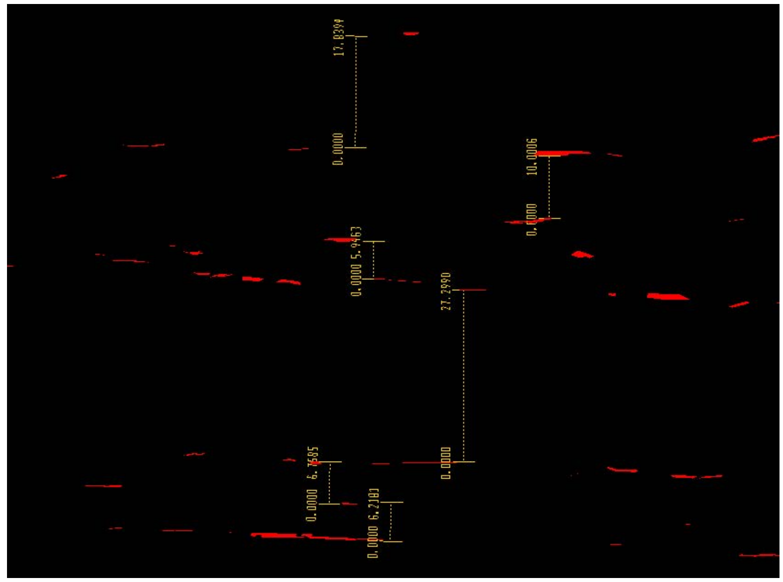


Figure 9

Surface to subsurface geologic interpretation (Lyons-Baral, 2014).

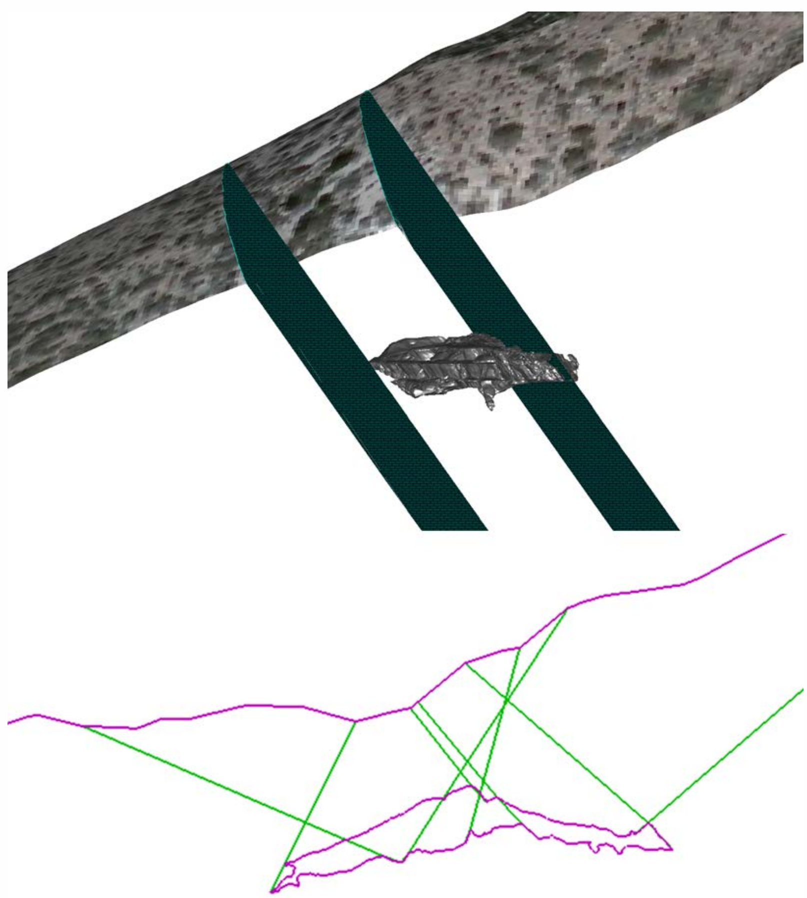


Figure 10

Rockfall simulation trajectories of LiDAR-based cross section (Kemeny et al., 2015).

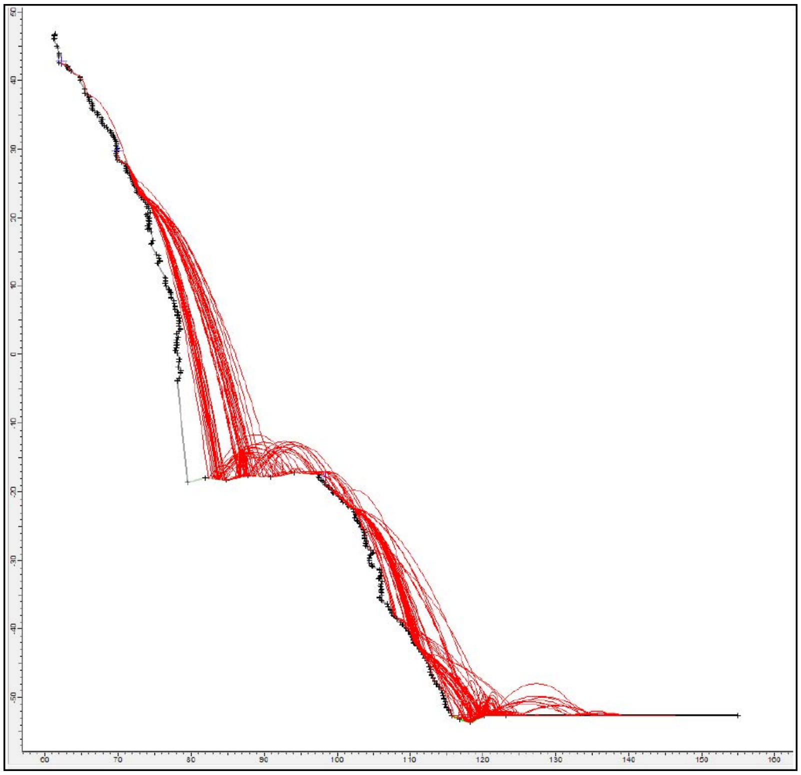
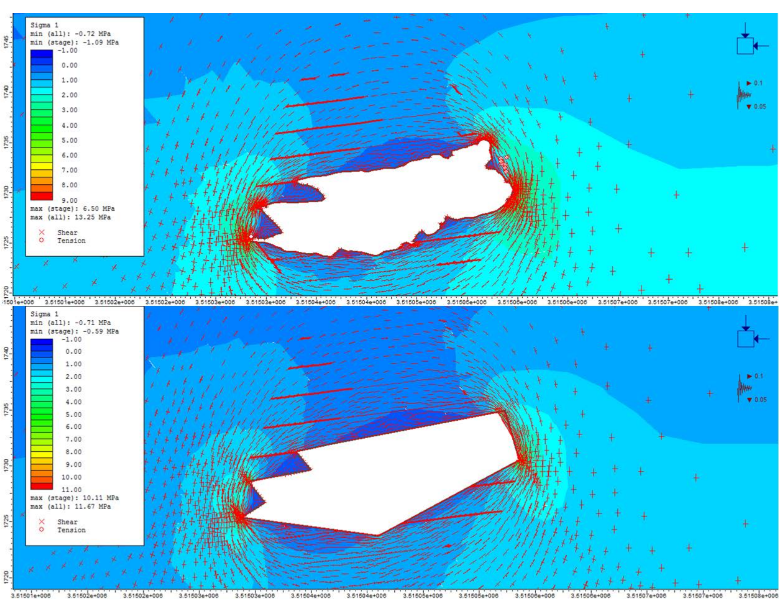


Figure 11

2D stress modeling showing difference in predicted failed rock mass and joint elements between a LiDAR-based cave polygon and a low-resolution digitized polygon (Lyons-Baral, 2014).



to the original designs (Figs. 12 and 13) (Lyons-Baral, 2015). The comparisons can be visually inspected and also quantified. Difference distances, areas and volumes can be calculated in both 2D and 3D to generate individual and accumulated reports of as-built versus design.

Monitoring. Monitoring natural and man-made earth structures typically means change detection. This method compares temporally spaced point clouds for the same locations and highlights the points or volumes that are not where they were since the previous scan was taken. With a simple workflow, rock mass deformation and failure can easily be discerned. Results reveal volumetric differences and displacement vectors, which, of course, can be converted to velocities and accelerations to predict time of failure. For basic monitoring, slopes or tunnels can be viewed periodically and movement areas will be colored differently than the previous time frame by colors for "forward" and "backward" motion (Fig. 14) (Kemeny et al., 2015).

Although change detection is typically a 3D operation, slope audits are typically looking for changes in 2D sections to monitor slope deterioration and damage. Figure 15 shows how an original pit slope design can be compared to the current state of the bench to see how much infilling has happened. With multiple temporal scans of this bench, the rate of bench infilling can be determined and a time to hazard can be determined, when the bench will no longer effectively catch rockfall.

In addition to being useful for monitoring of rock masses for deterioration over time due to natural time-dependent processes, it is extremely beneficial for rock control around active working areas in mines. Blasting, excavating and hydrologic changes are all factors in mines that need to be carefully monitored to ensure they are not damaging currently stable earth. Change detection from point clouds is a safe, fast and relatively cheap method for doing this. Pre- and post-blast scans of benches and highwalls can reveal fly-rock throw and bench face deformations (Wiseman and Rorke, 2015).

Forensic analysis and reverse engineering. Point cloud data are perfect for post-failure forensic analysis and reverse engineering. The high level of detail, continuous mapping of sites and ability to extract difference displacements and volumes is essential to effectively analyze a slope failure or tunnel collapse. With point cloud generated surfaces, pre-failure slopes and rock masses can be recreated to determine the failure mechanisms and the potential flaws in the design (Fig. 16) (Lyons-Baral, 2014).

After reconstructing the rock mass, various analysis methods can be used to narrow down the possible causes of the failure. With the point

Figure 12

Slope design (grey) versus as-built (green).

cloud providing actual failed mass volumes and shapes, as well as the geologic and geotechnical interpretation and characterization of the parent rock mass, most parameters are known when looking at kinematics and stress-strain analysis. Point clouds could even be useful to highlight moisture content in the rock mass by analyzing the reflective intensity. The number of variables that can be determined from the point clouds reduces the number of possible trigger variables down to increase the likelihood of finding the cause of the event.

The future

The future for point cloud uses in geotechnical engineering and other geological endeavors lies in more automation and data connectivity. Currently, some 3D software can automatically generate polygons for fracture patches of similar orientation which can then be plotted to stereonets for joint set determination as shown in Fig. 7 (Split Engineering, 2014). Other 3D software already has the ability to find breaklines (lines of greatest inflection/curvature) in the topography of point clouds, allowing for openpit mine crest and toe delineation, to find offset fault lines and to extrapolate engineered structure edges (Technodigit, 2014). And GIS software is excellent for both of these operations in continuous 2D surface models and can also generate polyline and polygon streamlines, sinkholes and hydrologic catchment basins.

To take this to the next level, software companies need to integrate all of this data into a 3D format that can relate all of the available data for analysis, predictive modeling and engineering design. Having the ability to use the power of both 2D and 3D automatic geometry and data extraction in one system will be the key to usability. Readily joining cyberinfrastructure community databases of publically available geologic and governmental data with the field-based mine data will be a crucial development to taking full advantage of technology (Mookerjee et al., 2015). Being able to easily analyze 2D and 3D spatially correlated raster (gridded), vector (point, polyline and polygon geometry) data, and block model data in one tool, or set of tools, with full integration, will create a huge leap forward in the value of point clouds in geotechnical and geological workflows.

To picture the future, imagine an openpit mine with at least daily UAS scanning, looking at the entire pit, highwalls, stockpiles, waste dumps and tailings dams. Scans will also be conducted for each blast. All point cloud and surface data will be ranked and validated, allowing users the ability to choose the time frame of data they want and the quality. Point clouds and surfaces for any time frame will be available over internet web viewers so that anyone can easily access the data from anywhere over their phones, tablets or computers. This data will then be used to monitor the slopes for recent movement and to get accurate stockpile and muck pile volumes. Geotechnical and geological fracture, fault, stratigraphic and hydrologic features with important attributes will also be automatically extracted from the

Figure 13

Overbreak and underbreak shown as colored surfaces and isopach contours (Lyons-Baral, 2015).

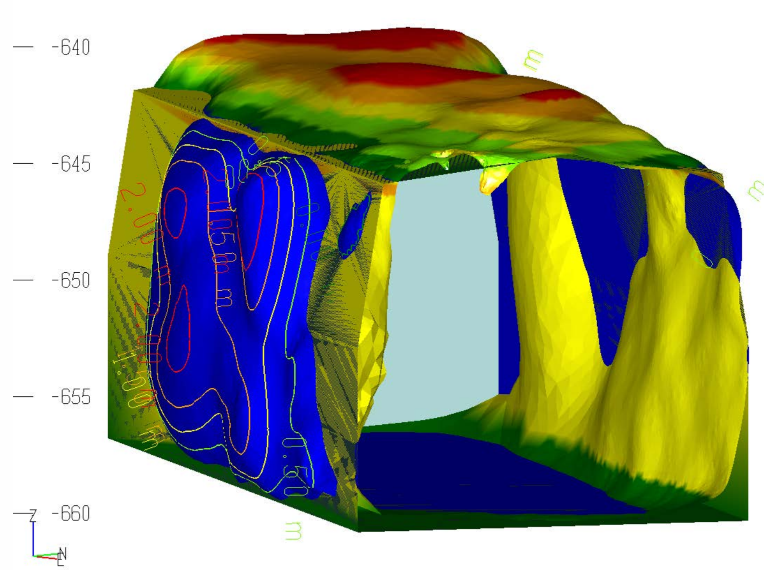
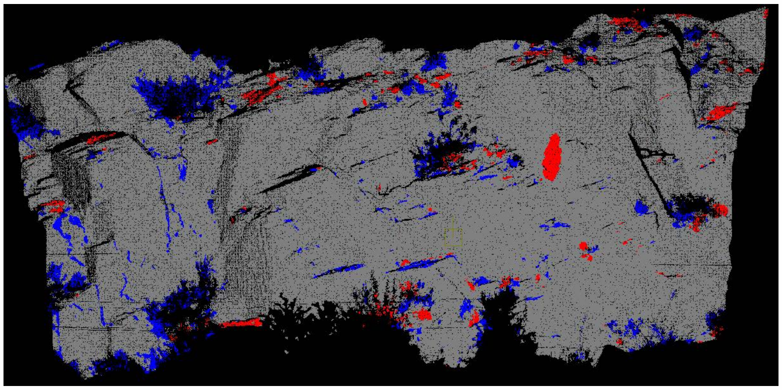


Figure 14

Change detection cloud showing rock mass gain (blue) and loss (red) (Kemeny et al., 2015).



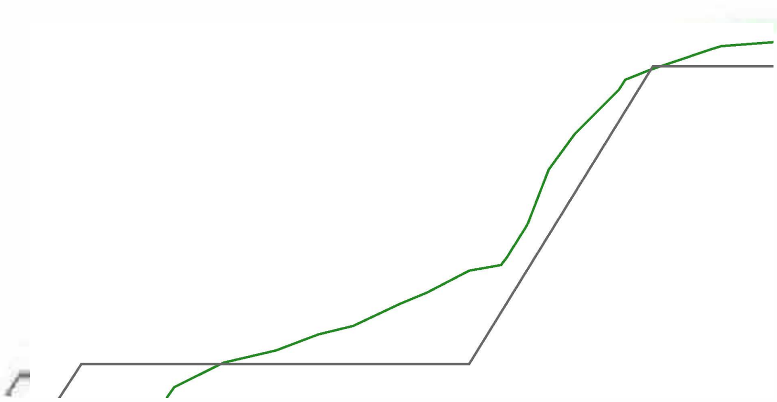
point cloud data. This attributed vector data will then be combined with continuous GIS raster models, GIS attributed vector data, 3D block models populated with drillhole and well data interpolated into all blocks. The data sources will be from the mine itself, but also merged with public geologic and governmental databases. A complete 3D and 2D visual inspection of the entire mine's data is immediately available and quickly rendered for inspection and workability. Statistical analyses will be conducted to find correlations of significant data relationships and controlling variables in geomechanical and geological processes. Online web viewers will again allow all stakeholders the opportunity to access the analyses and make decisions regarding operations. Optimization of mining operations and planning will be continuous based on the analyses of all data, allowing millions of dollars to be saved regularly, quickly paying for the investment in the hardware and software requirements of the system (Hexagon Mining, 2015).

Conclusion

In the recent past, point cloud advocates apologetically informed everyone that the technology is amazing, but slow, expensive, heavy, and difficult to process. We have finally come out of that growth period and point cloud technology is ready for everyone to use and use quickly. Geotechnical engineers and engineering geologists can gather so much more data, so much faster, process it so fast, analyze it thoroughly, and interpret, characterize and predict rock mass properties and behaviors. The future will be about bringing more data sources into one picture, one interpretive model, and one analysis to utilize all of the varied resources at our disposal to create a complete picture of the geology underfoot or over your head. ■

Figure 15

Slope auditing for bench infilling.



References

Alexander, S.C., Rahimi, M., Larson, E., Bomberger, C., Greenwaldt, B., and Alexander Jr., E.C. (2013), "Combining LiDAR, aerial photography and pictometric tools for karst features database management. In: (Lewis Land, Daniel H. Doctor and J. Brad Stephenson editors) NCKRI Symposium 2 Proceedings of the 13th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst," Carlsbad, New Mexico, published on-line by NCKRI, Carlsbad, NM, p. 441-448.

CISRO (2014), "Autonomous Systems: Zebedee," Retrieved on November 29, 2014 from https://wiki.csiro.au/display/ASL/Zebedee.

De Waele, J., Gutierrez, F., Parise, M., Plan, L. (2011), "Geomorphology and natural hazards in karst areas: A review [Editorial]," *Geomorphology*, 134, pp. 1-8.

Enge, H.D., Buckley, S.J., Rotevatn, A., Howell, J.A. (2014), "From outcrop to reservoir simulation model: Workflow and procedures", Geosphere, V. 3, No. 6, pp. 469-490.

5. Griffith, A.W., Becker, J., Cione, K., Miller, T., and Pan, E. (2014), "3D topographic stress perturbations and implications for ground control in underground coal mines," *International Journal of Rock Mechanics and Mining Sciences* 70, 59-68.

Haneberg, W.C., Norrish, N.I. and Findley, D.P. (2006), "Digital Outcrop Characterization for 3-D Structural Mapping and Rock Slope Design Along Interstate 90 Near Snoqualmie Pass, Washington," *Proceedings 57th Annual Highway Geology Symposium*, Breckenridge, CO, September 27-29, 2006.

Hexagon Geosystems (2015), "HDS Laser Scanners & SW", Retrieved on September 29, 2015 from http://www.hexagon.com/en/Geosystems.htm.

Hexagon Mining (2015), "MineSight (Version 10.5-02)" [Computer software], http://www.hexagonmining.com/mine-planning.htm.

Hodgetts, D. (2013), "Laser scanning and digital outcrop geology in the petroleum industry: A review," *Marine and Petroleum Geology*, 2013 July; eScholarID: 202247.

Hubbard, S.S., Gangodagamage, C., Dafflon, B., Wainwright, H., Petersen, J., Gusmeroli, A., Ulrich, C., Wu, Y., Wilson, C., Rowland, J., Tweedie, C., Wullschleger, S.D. (2013), "Quantifying and relating land-surface and subsurface variability in permafrost environments using LiDAR and surface geophysical datasets," Hydrogeol J, 21(1):149–169.

Kemeny, J. and Kim, C. (2009), "Increasing our understanding of time-dependent rock mass behavior with ground-based LIDAR, 3D discontinuum modeling, and fracture mechanics," *Rock Mechanics,* Fuenkajorn & Phienwej (Eds) © 2009, pp. 35–53.

Kemeny, J., Combs, J., Lyons-Baral, J. and 9 others, (2015), "Application of three-dimensional laser scanning for the identification, evaluation and management of unstable highway slopes." Final Report, Pooled Fund Project TPF-5(166), Arizona Department of Transportation, 2012.

Lyons-Baral J, (2012), "Using terrestrial LiDAR to map and evaluate hazards of Coronado Cave, Coronado National Memorial, Cochise County, AZ," Arizona Geology Magazine, Summer 2012: 1–4, Accessed at http://azgeology.azgs.az.gov/article/earth-science/2012/08/using-terrestrial-lidar-map-and-evaluate-hazards-coronado-cave/page/0/1.

Lyons-Baral, J. (2014), "Coupling Surface and Subsurface LiDAR Scanning for Improved Geomechanical Interpretation, Characterization and Modeling," Master Thesis, University of Arizona, unpublished.

Lyons-Baral, J. (2015), "Introducing The Point Cloud Mesher," Hexagon Mining – MineSight, Newsletter, April 2015, http://www.minesight.com/en-us/company/newsletters/apr2015/pointcloudmesher.aspx

Mookerjee, M., Vieira, D., Chan, M., Gil, Y., Goodwin, C., Shipley T. and Tikoff, B. (2015), "We need to talk: Facilitating communication between field-based geoscience and cyberinfrastructure communities," *GSA Today*, Nov. 2015, Vol. 25, # 11, The Geological Society of America.

RIEGEL (2014), "Products," Retrieved on November 29, 2014 from www.riegel.com.

Split Engineering (2014), "Split FX: Point Cloud Processing Software (Version 2.3)," [Computer software]. http://www.spliteng.com/products/split-fx-software/.

Technodigit (2014), "3DReshaper: the 3D Scanner Software (Version 2014 MR1)," [Computer software]. http://www.3dreshaper.com/.

Wiseman, T. and Rorke, T. (2015), "Using Photogrammetry and UAVs for Pattern Optimization, Quantification and Mapping," *The Journal of Explosives Engineering*, September/October 2015.

Figure 16

Ability to volumetrically replace fallen blocks and matching joint structure (Lyons-Baral, 2014).