

Integrated rockmass characterization and stability modelling for tunnels using LiDAR



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ABSTRACT

Despite operational constraints, rock tunnel construction projects require a solid understanding of rockmass conditions in order to effectively design excavation and support methods. Where tunnel instability is governed by structural discontinuities, LiDAR or 3D laser scanning technology shows great potential to complement current assessment techniques. LiDAR scans of the rock face offer digital documentation of rockmass conditions from which an interpreter can extract a large quantity of structural data. The authors propose a workflow for applying LiDAR scan data to 3D discontinuum modelling for practical design outputs.

RÉSUMÉ

La construction de tunnel en roche demande des précises informations géotechniques pour prévoir les conditions futures. À présent, la méthode de rassembler des informations geo-structurelles est beaucoup limitée par accès aux sections de roche non-soutenuees. LiDAR, une technologie seulement récemment appliquée à la géotechnique, montre beaucoup de potentielle pour nous aider à mieux décrire la condition du sol. Le module de balayage 3D utilise un faisceau laser pour identifier des millions de points, créant une scène géométrique à trois dimensions de ses entours. La recherche présentée propose une façon d'utiliser les données des balayages lasers pour produire des modèles numériques à trois dimensions plus représentatives qu'avec les méthodes traditionnelles.

1 LIDAR FOR GEOTECHNICAL ASSESSMENT

Construction projects involving geotechnical work require detailed site data in order to progress on time and on budget. Contractors and consultants that collect site data continually search for cheaper, more efficient and more precise methods of collecting data that do not interrupt construction progress. Developing technologies sometimes offer an increased quantity of more accurate measurements, but do not fit operationally and thus remain confined to research applications. Collecting geotechnical data for rockmass characterization of rock tunnels remains a challenge. Characterization pre-construction tends to be limited to borehole data and nearby out-crops. With limited access to and time at the face during construction, rock characterization remains very qualitative and subjective in practice with heavy reliance on empirically-calibrated rockmass assessment schemes such as Q, RMR and GSI (Barton et al. 1974, Bieniawski 1978, Hoek and Brown 1997); thus there remains room for improvement. The authors propose LiDAR, Light Detection And Ranging, technology as a source for detailed rockmass data collection as the tunnel advances, with the potential for this data to be integrated into highly representative 3-dimensional numerical rockmass models. This paper provides an overview of the recommended strategies for data collection, processing and data extraction, as well as integration into 3D discontinuum models.

LiDAR scanners use a rotating laser scanning system to create a 3D image of the surrounding area composed of millions of points in space, called the "point cloud". For each data point, the scanner emits a laser pulse in a known orientation. The object it strikes sends a return

signal and using either time-of-flight or phase-shift analysis the scanner determines a distance to the object. This process occurs up to 500,000 times per second (depending on the scanning technology) and can thus create a detailed geometric re-creation of the area with very accurately positioned points in a short amount of time. LiDAR technology has widespread implementation in the chemical and automotive industries to support equipment placement in factories and product quality assurance. It is due to the increasing robustness of the scanners and recent technological advances allowing for quicker scanning that has led to their implementation in geo-hazard assessment (Ferrero et al. 2009, Slob et al. 2005) and underground environments (Decker 2008). However, the implementation of LiDAR underground has primarily been confined to as-built tunnel models and contract verification. While these operational applications are diverse and significant, as demonstrated by Fekete et al. (2010), the opportunity to use detailed rockmass information for geo-mechanics applications has yet to be explored. The following sections detail the process by which geotechnical staff for underground projects can begin to capitalize on this opportunity.

2 DATA COLLECTION IN AN ACTIVE TUNNEL

The work presented is based on the LiDAR scan data collected at the face of active drill and blast railway tunnels. The ability to collect data within the excavation cycle has many advantages, including the permanent digital documentation of rockmass conditions that will be later obscured by liner installation. Further, the digital documentation is not restricted by accessibility to the

face of personnel mapping geo-structural data. LiDAR scanning was performed in five headings(10-15 m diameter) of a railway tunnelling project near Oslo, Norway in a collaborative research effort between Queen's University (Kingston, Ontario) and the Norwegian Geotechnical Institute (NGI). The scanning of three completed unlined rock tunnels (4-8 m diameter) was also undertaken in order to assess techniques across a range of structural styles and rockmass character.

A stationary tripod setup was used and scanning at active tunnel sites occurred after blasting, mechanical scaling and manual scaling. The tripod was set up at the limit of supported rock, approximately 7 m from the face; 0.5 to 1 diameter from face is optimal. Scans were performed with the Leica Geosystems HDS6000, a phase-based scanner with a 360° degree horizontal field of view and 310° degree vertical field of view. The system is a high accuracy system, calibrated to have sub-millimeter ranging error. This system has a high collection rate of up to 500,000 points per second, making it ideal for quick deployment in an operational tunnel environment. Tripod setup, scanning and take-down could be completed within five minutes. Fig. 1 shows deployment of the 3D laser scanner at the railway tunnel operation near Oslo.



Figure 1. LiDAR data collection with tripod setup in active 10 m diameter drill and blast railway tunnel.

3 DATA PROCESSING AND FEATURE EXTRACTION

LiDAR scanning creates a 3-dimensional point cloud made of millions of points each attributed with (x, y, z, i) information. The (x,y,z) coordinates position the point in space relative to the scanner and the (i) is an intensity value that is a function of the surface reflectivity. The intensity value can help the interpreter distinguish between bright, reflective objects and dark, absorbing objects in the scan. One example of operational applications of intensity differences is to detect wet shotcrete patches due to liner leaking in tunnels (Fekete et al 2010). An example of the raw point cloud collected with a LiDAR scan of an unlined test tunnel is found in Figure 2.



Figure 2. Raw point cloud data collected in unlined rock tunnel, 8 m diameter (Oslo, Norway).

3.1 Data Processing

As described in Fekete et al.(2008), the LiDAR scan data should be edited to reduce to the area of interest due to the computational demands of these large files(up to GBs in size). For the work presented, the Innovmetrics Polyworks (2008) software package was primarily used. Surface models created by constructing a meshed surface from point data can help make manipulating data more practical and will allow for surface comparisons, for example assessing shotcrete thickness (Fekete et al. 2010). As mentioned previously, the ability to digitally document the rockmass before it is obscured by liner instalment is of great benefit. The ability to add, or "align", these digital rockmass datasets together provides an excellent resource for rockmass assessment, particularly for extracting geo-structural entities. Figure 3 shows surface models of three 5 m rounds of excavation of a 10 m diameter railway tunnel. These models have been aligned to each other by matching supported zones back from the face that are captured in each scan and have since been edited out.

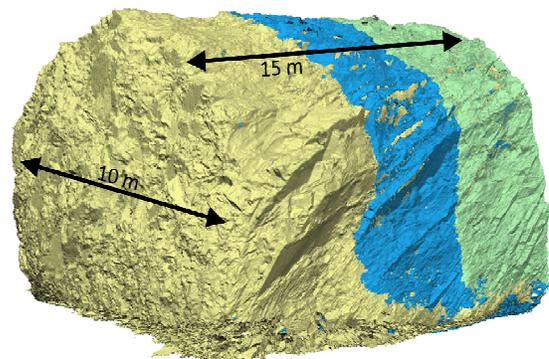


Figure 3. Surface model of LiDAR data for three aligned 5 m excavation rounds showing rock structure, tunnel face seen obliquely from the "rock's perspective" looking into the tunnel.

3.2 Geological Feature Extraction

Rockmass characterization with LiDAR scan data requires the extraction of geological features from the surface models or raw point clouds. Information that can be extracted includes joint orientation, joint spacing and strength estimated by roughness. Geotechnical data extracted from LiDAR scans as a complement to traditional mapping is superior to hand mapping alone in that it can retrieve a greater quantity of discontinuity measurements not limited by access to the face or crown, each of which is also assigned a position in 3D space. The ability to retain position information is significant both because spacing of joint sets can be quantitatively assessed back at the office rather than subjectively in the field, as well as, providing the ability to spatially position major discrete feature, such as faults. Planar discontinuities can be extracted interactively from LiDAR data by fitting a plane to a user-selected area of points. Geometric data of the plane can be used to calculate dip, dip direction (or strike), and centroid.

The surface model for a 5 m round of excavation in a 10 m diameter tunnel is shown in Figure 4 with several identified discontinuity planes intersecting the model. Figure 5 shows that an interpreter can use tricks such as artificial lighting to view the data and more easily identify joints sets and assess their spacing. Figure 5 shows a pervasive joint set along tilted bedding that is a prominent sliding plane in the left sidewall.

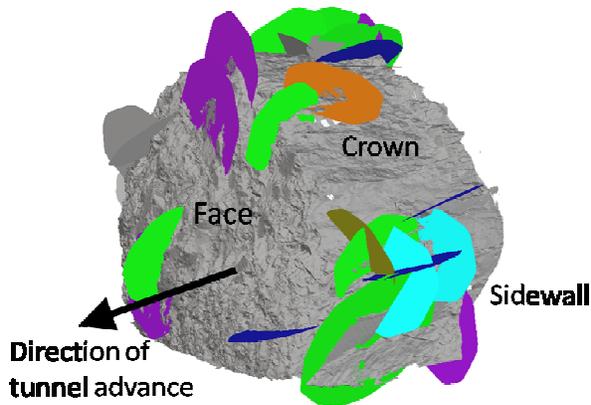


Figure 4. Oblique view of LiDAR surface model with intersecting joint planes in a 5 m excavation round of an active tunnel heading. Joints are coloured according to orientation to help visually identify sets.

Because point cloud software has been developed with other markets in mind, many operations a geotechnical engineer would like to perform can be time-consuming and troublesome. Some software packages have attempted to automate feature extraction, some with direct stereonet output. While this can greatly reduce the time required for feature extraction, current algorithms are really only suited to rock outcrops with obvious structural features. Also, some meshing algorithms cannot handle fully 3D datasets required for

tunnels. Furthermore, such automation cannot discern between blast-related damage and natural features. The authors stress that while interactive feature selection will more effort-intensive, it is the best way of ensuring that extracted data represents the true rockmass character. It is recommended that the interpreter has visited the site and has an intuition for the rockmass structure. The authors find that a geotechnical engineer with experience at the site has a much greater ability to verify extracted features as well as calibrate numerical models that are later built from this data.

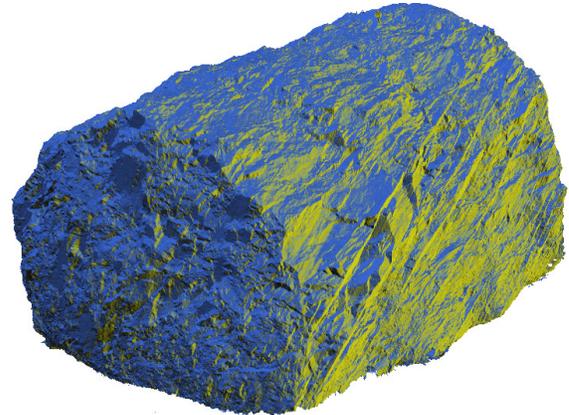


Figure 5- Oblique view of LiDAR surface models for three 5 m rounds of tunnelling, where artificial lighting to highlight structure due to tilted bedding in the left sidewall.

4 INTEGRATING LIDAR DATA INTO 3D DEM MODELLING

With LiDAR-derived structural data, the geotechnical engineer has the ability to more accurately represent the rockmass in numerical modelling. This representativeness is a function of a greater quantity of measurements throughout the exposed heading, due to relieved accessibility and time constraints. Discontinuum modelling of excavation rockmasses is most appropriate in blocky to very blocky conditions under moderate to low stress, where failure along discontinuities is most likely (Hoek et al. 1995). The accompanying positional information of each discontinuity gives the modeller additional power. He or she can either use planes in their actual position in space, or to analyze the planes relative to each other to perform statistical analyses of spacing and its variability. The authors will discuss the integration of LiDAR into 3D discrete element models (DEM) with respect to two distinct methods, defined as follows:

Deterministic reconstruction

a jointed rockmass model with discretely measured discontinuities in LiDAR data, each with specified orientation and position, and

Statistical reconstruction

a jointed rockmass model with selected statistical parameters based on interpretation of discontinuity data into sets with statistically variable orientation and spacing.

As will be discussed, these two methods offer complementary ways for the geotechnical engineer to understand past structural failures and predict future challenges. The two methods are constructed in different ways and are accompanied by distinct advantages and disadvantages.

The models presented are distinct element models created in 3DEC (Itasca 2004). The use of rigid blocks in these models is justified by shallow tunnel depth (low stress) and a blocky rockmass where failure is dominated by jointing. For numerical stability, a minimum cut length tolerance is specified.

4.1 Process for Deterministic Reconstruction

The deterministic method requires only the data management of joint orientations and location. Unique joints are input into the rockmass model at the exact position they were encountered in the tunnel. As a result, discontinuities are focused around the excavation and the density of jointing decreases into the more distant rockmass. Joint strength parameters, either based on roughness assessment, lab testing or past experience with the rockmass, are applied to the joints.

4.1.1 Challenges Associated with Deterministic Models

One would assume that the greater the quantity of joint planes extracted, the more representative the reconstructed rockmass. However, the LiDAR data interpreter must be wary of "re-picking" the same discontinuity plane when it appears as a joint surface in more than one position (i.e. crown and sidewall). Using double-counted discontinuities in the deterministic model can lead to computationally challenging, non-real narrow wedges and a concentration of small blocks around the tunnel opening. The authors therefore recommend that LiDAR data interpreters proceed cautiously when identifying joints. For the results presented, redundant joints were visually filtered out by extrapolation before feature attributes were extracted from the point cloud processing software. The interpreter ensured that if planes did intersect the model in more than one location, it was not identified as a distinct joint entity. Coded algorithms may facilitate this process of identifying unique joints in the future.

The assignment of persistence parameters to 3DEMs also remains a challenge. A method for assessing joint persistence or discontinuity size from LiDAR scan data has yet to be proposed and so values remain difficult to calibrate. Exposed joint surface area is easily calculated in LiDAR data and may be helpful as a guide, but such areas may greatly underestimate actual discontinuity size. Joint traces, which have traditionally been used for discontinuity size evaluation (Priest 1993), are difficult to track in LiDAR data and thus make conventional analysis challenging.

Given that each discontinuity used in the deterministic method is 'real', one might be tempted to not limit joint persistence. However if constructed joints are fully persistent, this can greatly underestimate rockmass stability. The persistence parameter in Itasca's 3DEC functions as a percentage of successful cuts; for a persistence of 0.8, 80% of the block cuts to be created with a specific joint are successful, the remainder staying joined. The authors have constructed models over a

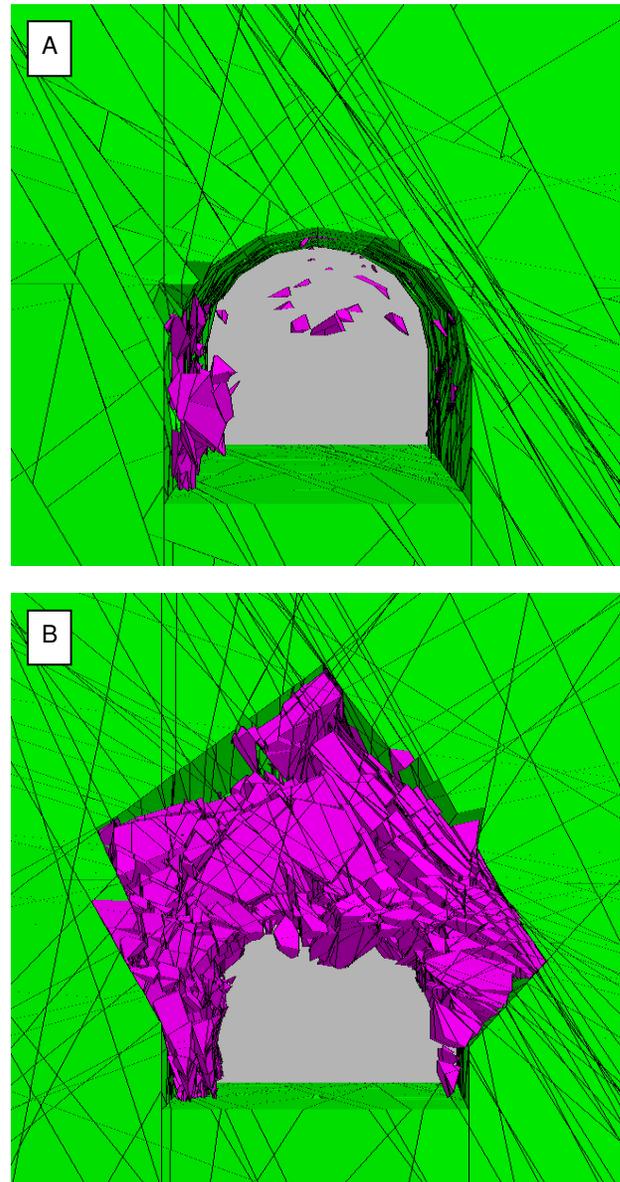


Figure 6- Two examples of deterministic models illustrating the range of failure depending on persistence, with purple blocks having exceeded the 1 cm displacement threshold. A) Deterministic model with 47% persistence resulted in 17.8 m³ of displaced rock and B) Deterministic model with 100% persistence resulted in 515.6 m³ of displaced rock

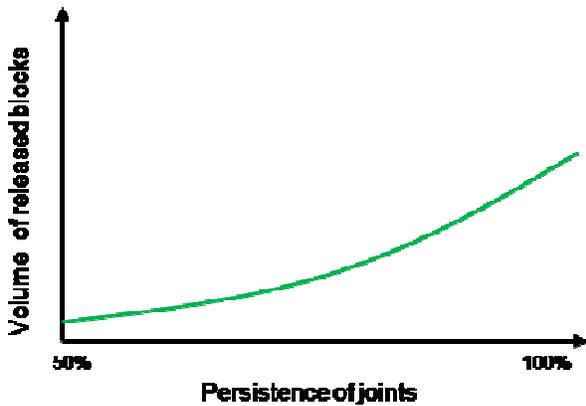


Figure 7. Schematic of the dependence of 3D rockmass model stability (measured by released blocks from excavation) on persistence parameter.

range of persistence and find that tunnel stability is very dependent on this parameter. Figure 6 shows a completed stability analysis for two deterministic models, one with full persistence and one with low persistence. A schematic for the effect of persistence on a simplified rockmass model is found in Fig. 7. The results of a more thorough investigation of numerical model sensitivity will be presented in following publications.

Another challenge with the deterministic reconstruction is bias based on the scanner's restricted ability to collect data points on surfaces of all orientations in all positions of the tunnel. In order for a plane to be identified, several LiDAR data points must fall on the surface. This is not always possible if the surface is obscured due to excavation geometry or if the surface lies in a plane parallel to the scanner's line of sight. This type of bias has been well documented for rock outcrops (Sturzenegger 2007), and methods for correction have been developed (Lato et al. 2010). However, the added complexity of retrieving data from 3 roughly orthogonal surfaces has yet to be assessed. A schematic of bias for LiDAR collection at the tunnel face is shown below in Fig. 8a. This image highlights that the sidewall, crown and face have varying ability to identify a particular joint orientation. Fig. 8b illustrates that even with the same orientation, the ability to capture it in a 3D scan varies based on location, due to the changing orientation relative to the scanner's line of sight.

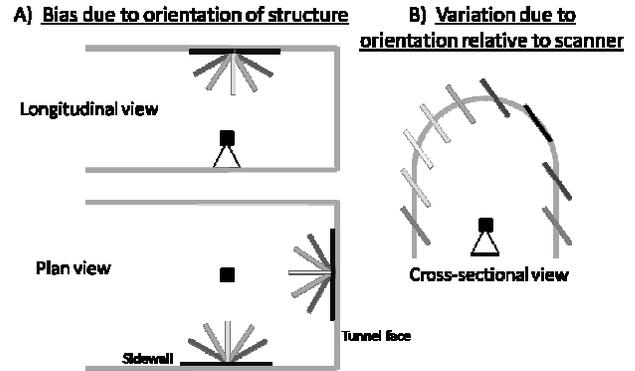


Figure 8: A- Schematic of bias in LiDAR scan due to orientation of joint structure and where it occurs in the tunnel. B- Schematic of bias due to changing position. Dark lines would have best sampling and light lines would have the worst.

Thus, the authors find that it is not reasonable to expect the laser scanner to detect all joint surfaces with a single scan. For road outcrops, research finds that bias can be greatly reduced if scans are performed from more than one location and using the aligned data (Lato et al. 2009). However, this does not seem a likely solution for underground scanning. Most underground openings are narrow with not much room for moving the tripod a great enough distance to significantly change which discontinuities are visible to the scanner. The setup position is further restricted when working at the face by the extent of unsupported ground. Finally, with imposing operational constraints and schedules that must be met, additional scanning time may not fit into allotted geotechnical investigation time. Thus, should deterministic reconstruction be selected, the modeller must accept that the influence of bias on collected data is significant and that all visible joints are not being identified. One way to help mitigate bias is to reject the use of discretely measured features in modelling and opt rather for statistical reconstruction.

4.2 Process for Statistical Reconstruction

In comparison to the deterministic method, statistical reconstruction requires additional model construction steps and increased user interaction. This interaction is powerful in that the interpreter can elect to coordinate his or her interpretation to the geological context, but with this power comes responsibility. The danger of increased interpretative power is for 3D block modelling to return to the highly subjective form it takes with traditional joint mapping; in other words, negating the benefits of a large database of highly accurate LiDAR-extracted features. However in order to surmount the bias issues discussed as well as for representative jointing to further penetrate the rockmass, the statistical method must be undertaken. Discontinuity orientation data is interpreted via stereonet into joint sets with statistically defined orientation variability. The similarity between traditionally mapped joint data and LiDAR data that has been statistically

interpreted has been demonstrated (Fekete et al. 2010). The advantage of the statistical sets is that they better describe variability within the sets as well as capturing more randomly distributed sets. The construction of an artificial joint complex with the interpreted statistics with a utility such as JDIST in DIPS (RocScience v 5.1, 2008) may be helpful to confirm the suitability of statistical characterization. Some “sets” with highly variable orientation may be required to capture random fracturing in the rockmass.

In addition to orientation, the statistical reconstruction requires the spacing of each set. This can be determined by analyzing isolated joints sets either in point cloud processing software or after extracting the data. Fekete et al. (2010) provides an example of such an analysis. Both the average spacing value and its variability should be considered. Due to the bias issues discussed, the authors do not recommend the average spacing as the go-to value. The interpreter should recognize that, if joint plane redundancy filtering has been properly conducted (as discussed in 4.1.1), the omission of obscured joint planes is more likely that joint plane duplication. This omission would lead to a range of spacing values. If on-site inspection at the time of scanning identifies a consistently spaced set, the interpreter should therefore opt for the low-end value rather than the average.

Similar to the deterministic method, there is no defined way to select persistence values for a statistic model. Here the interpreter may use block size and joint surface area as guides to calibrating assigned persistence values. The images of two models for the case-study rockmass, a tilted sedimentary unit, are shown in Fig. 9; they highlight that a range of spacing and persistence can be interpreted from a given data set.

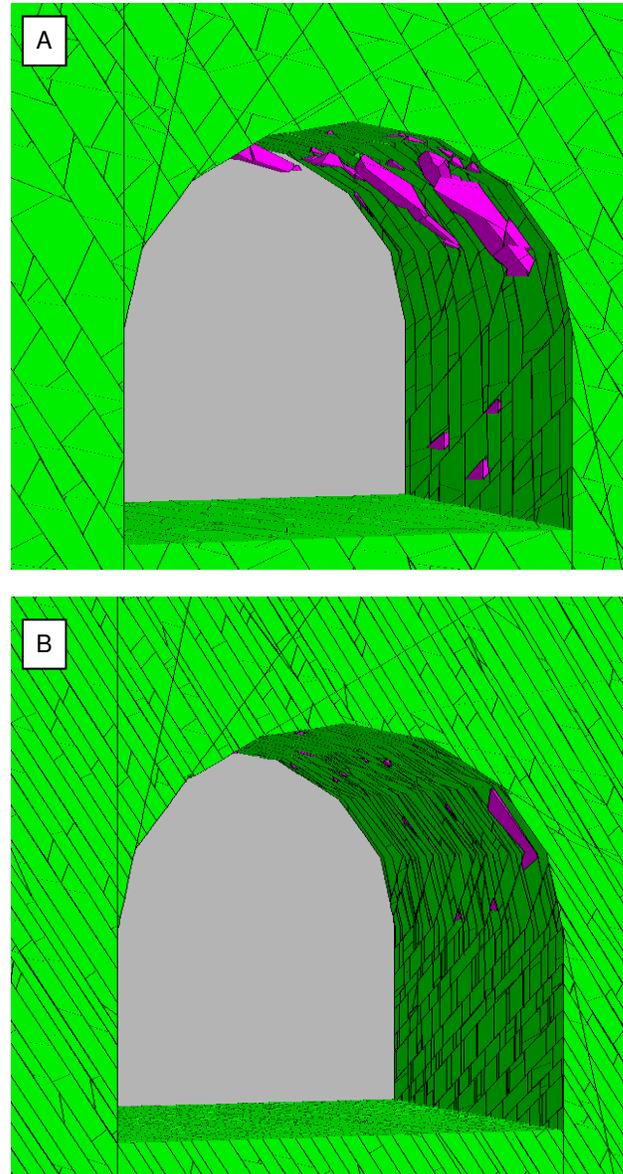


Figure 9. Statistical reconstructions of a tunnel in a tilted sedimentary rockmass. *A*- Widely spaced major and minor sets, with high persistence. Displaced block volume is 2.036 m³ from 47 blocks. *B*- Tightly spaced major joint sets and moderate persistence. Displaced block volume is 0.196 m³ from 27 blocks

5 DISCUSSION LIDAR-BASED 3DEM MODELLING METHODS

5.1 Comparing the Statistical and Deterministic Methods

As already evident in discussing their construction process, the deterministic and statistical methods have differing strengths and weakness, and are best applied with different modelling objectives in mind.

The deterministic method is advantageous in that it represents real, discrete structural features which may not be captured in rockmass characterization

classification. This would be especially beneficial when a feature such as a weak fault zone is critical to tunnel stability. In other words, where stability is governed by non-repeatable, unpredictable structure, deterministic is far more appropriate. Furthermore, the deterministic method is ideal for revisiting completed tunnel sections with overbreak to assess the contribution of structure. A better understanding of structural attributes (orientation and spacing) and resulting block sizes allows for a re-evaluation of tunnel support. As well, a deterministic reconstruction concentrates cuts near the excavation, i.e. the zone of interest, and thus computing time is not 'wasted' in creating and evaluating distal blocks. In other words, the deterministic model offers an economy of joint density. This is of even greater concern if deformable blocks are to be used.

However, the deterministic method's disadvantages are equally diverse. This method is less likely to characterize general rockmass character. While suitable for back-analysis, it is a less adequate predictive tool for design. Furthermore, if a joint selection is not put under enough scrutiny, the stability analysis might falsely point to instability along blast damage surfaces that have been misinterpreted as natural discontinuities.

Statistical rockmass reconstruction is advantageous in that it is more appropriate for general rockmass stability rather than a particular section of tunnel. In statistically analyzing the data and reconstructing average spacing and orientations, the user has the ability to consider structure deeper within the rockmass. This is a significant benefit if larger block release volumes are anticipated in unsupported ground, ex. in a weak very blocky rockmass. While interactive picking of discontinuities in LiDAR data is currently user-dependent and therefore leaves room for misinterpretation, statistical models help to reduce the impact of any one stray measurement. Finally, the reduced influence of bias in data can be seen as a great advantage if the interpreter is experienced enough to understand and cope with variability created by bias.

Conversely, the disadvantage of a statistical reconstruction is that it does not make full use of the data collected: the actual location of discontinuity surfaces is discarded. Furthermore, it relies on the assumption that a statistical distribution accurately represents variability in orientation and spacing. Different distributions may be required for different data sets and caution should be maintained in attempting to fix one 'superior' method, Fisher K, random, exponential etc., especially when clustering appears to be anisotropic.

Thus the authors conclude that both methods have their limitations. Perhaps the optimal method requires a hybridization of the methods, or at the very least, constructing them in tandem, where the lessons of one model feed-back into the other. Research continues in this field.

5.2 Other Modelling Considerations

The authors wish to present some additional considerations for numerical modelling of tunnelling

conditions to stress the importance of staying true to the geological context. It requires little effort to simply input discrete joints into a block model (as with a basic deterministic model). One might expect representative results, but without considering geologic context this is unreasonable. There are many steps in the model construction process which require the modeller to understand the rockmass which he or she tries to recreate. It is for this reason that the authors place emphasis on the need for "ground-truthing". For example, the order in which joints are added to the block model is significant, particularly in lower persistence models; the first joints tend to be high persistence, because they intersect fewer other joints and thus tend to have fewer unsuccessful cuts, and the final joints tend to be much lower persistence. This effect is even more significant when joints are sorted by set and then input, because the first set becomes nearly fully persistent, as it would rarely intersect itself. But for the case-study rockmass presented, a tilted sedimentary unit, a dominant set along bedding fits the geological model well, and thus inputting discrete joints in a random order would be inappropriate. This special consideration to the order of joint construction must also be given when creating statistical models, though this is perhaps more obvious due to increased modeller control on model inputs.

As discussed in 4.1.1, there are challenges with assigning persistence values to DEMs. There does not appear to be a solid understanding in the literature of how persistence, as it is expressed in modelling packages such as 3DEC (a percentage of successful cuts), corresponds to measurable rockmass attributes. Future research should seek to fill in such gaps in understanding, especially considering the sensitivity of 3DEM.

5.2 Proposed Workflow and Integrated Feedback

In order for LiDAR to be integrated into rockmass modelling, the authors propose a workflow, from data collection through to design outputs (Fig. 10). The workflow helps to highlight the differences in the interpretation required prior to performing stability analysis, as well as, the differing design outputs that statistical and deterministic rockmass modelling provide. As discussed previously, the statistical method requires additional interpretation of extracted data, while the deterministic method's success relies on careful data checks. Pertaining to model outputs, the deterministic model is helpful in calibrating rockmass performance based on mode of failure and critical failure planes. The statistical model, however, is best suited to sensitivity analysis of parameters such as spacing. This analysis allows the modeller to identify the range of instability that is possible, the critical parameters to the rockmass performance, as well as the predicted block sizes. The ability to assess released block size and shape can further assist with support design, e.g. shotcrete vs. rock bolts (Kalenchuck et al. 2006). Statistically-built models would be attractive to those who wish to perform

probabilistic analysis because the LiDAR data offers a practical range of values from which to begin.

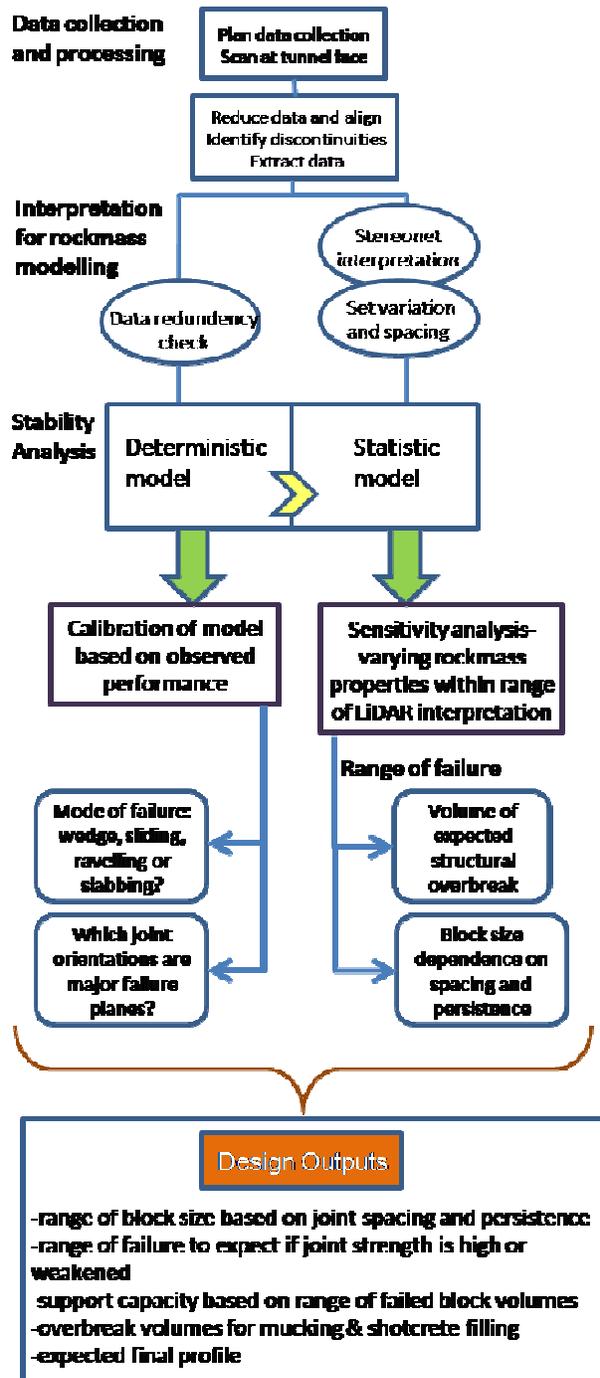


Figure 10- Workflow for implementing LiDAR structural data into representative, value-added numerical models.

A significant conclusion of this work is that geotechnical engineers seeking to integrate LiDAR data into rockmass modelling should not select one method or the other exclusively. As discussed above, each method has its advantages and disadvantages and provides differing outputs. Thus, the authors recommend that

feedback should exist between the models. Specifically, the deterministic model is helpful for calibrating failure mode and extent of failure against actual tunnel performance. Then the statistical method, once calibrated against rock performance with the deterministic method, will be better equipped to predict future tunnelling conditions and assess failed block volumes and block sizes. Together, these rockmass modelling methods provide very practical design outputs that are truly representative of the underground environment.

6 CONCLUSIONS

Geotechnical engineers are charged with the task of evaluating a rockmass and its potential modes of instability, clearly an important task, and yet time and access to the face are restricted by operational constraints. In order to adequately assess complex geological settings, numerical modeling is required, which demands many inputs. As demonstrated, interpreting LiDAR data provides supplementary structural data for jointed rockmasses. With known joint network geometry, geotechnical engineers may focus their efforts on calibrating representative models rather than intensive modeling efforts based on additional assumptions and simplification. Furthermore, LiDAR-based discontinuum modeling promotes a quicker pinpointing of failure mechanism rather than requiring many models which explore a variety of failure modes. With the mechanism identified, more effort can be put into assessing the extent of instability and then responding with appropriate support design.

It has been demonstrated that two primary methods for rockmass reconstruction offer different advantages and limitations. A workflow for integrating LiDAR rockmass assessments into stability modeling has been proposed, and relies on the outputs of both reconstruction methods, finding that they are complementary.

7 ACKNOWLEDGEMENTS

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