GEOTECHNICAL APPLICATIONS OF LIDAR FOR
GEOMECHANICAL CHARACTERIZATION IN DRILL AND
BLAST TUNNELS AND REPRESENTATIVE 3-DIMENSIONAL
DISCONTINUUM MODELLING

by

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Abstract

Contractors and tunnelling engineers consistently seek to identify techniques and equipment to improve the efficiency and lower the cost of tunnelling projects. Based on the recent successes of rock slope characterization with laser scanning techniques, the author proposes 3D laser scanning (LiDAR) as a new tool for geotechnical assessment in drill and blast tunnels.

It has been demonstrated that practical deployment of a phase-based LiDAR system at the face of an active tunnel heading is possible with a simple tripod setup. With data collection requiring only 5 minutes at the tunnel face, it was shown that this technique could be integrated into geotechnical evaluation without interruption of the excavation cycle. Following the successful scanning at two active tunnelling projects and two completed unlined tunnels, the research explored the applications of the data. With detailed geometric data of the heading as it advanced, the author identified applications of interest to the contractor/on-site engineer as well as the geotechnical engineer or geologist responsible for rockmass characterization. Operational applications included the extraction of information about tunnel geometry and installed support, while geomechanical information provided important elements of rockmass characterization. Building on the success of retrieving joint network information, the research investigated the potential for LiDAR-derived structural databases to be the basis for highly-representative 3D discrete element models. These representative models were found to be useful for back-analysis or as predictive tools for future tunnel design.

The primary implications of the thesis are that a) LiDAR data collection at the face of a drill and blast tunnel operation is practical and potentially has great value, b) data extraction is possible for a wide range of applications, and c) that discontinuum stability analysis becomes a
much more powerful tool with the integration of LiDAR data. The cumulative result of the work presented is a proposed workflow for integrating LiDAR into tunneling operations.
The thesis “Geotechnical Applications of LiDAR for Geomechanical characterization in Drill and Blast Tunnels and Representative 3-Dimensional Discontinuum Modelling” is the product of the formal research of Stephanie Fekete. However during the research, the support of Mark Diederichs and Matt Lato helped guide her ideas and writing. Complete references for submitted/published journal papers are included in Chapter 6: Summary and conclusions.
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Chapter 1

Introduction and background

1.1 Project motivation and overview

Underground construction is required for a vast range of civil infrastructure and energy industry projects including rail and road tunnels, water conveyance tunnels and hydro-power caverns, to name a few. All excavation projects are constrained by schedule and budget and are simultaneously held to high engineering standards. In order to efficiently excavate in rock, both with regard to time and cost, a detailed understanding of the rockmass properties and behavior is required. In addition to the data collected for the Geotechnical Baseline Report (GBR), geotechnical engineers on site must continue to evaluate the rockmass and monitor its performance. Continued evaluation of ground conditions allows site engineers to modify rock support or excavation method as changes occur in the rockmass character. In the case of an active drill and blast tunnelling operation, geotechnical evaluation is restricted by: the time allocated to assessment of the face (heading), safety in unsupported rock zones and ability to physically access exposed rock (potentially a small portion of large diameter tunnels). Often geotechnical assessments are limited to estimation of rockmass character with classification systems such as RMR (Bieniawski 1976) or Q (Barton et al. 1974). While these systems are well supported by case-study data for empirical design methods, a significant amount of detail potentially included in rockmass character descriptions is lost when values are quickly and broadly assigned within classification schemes. This is particularly true when detailed face mapping, including the documentation of geological structure, is not conducted regularly.
In the field of rock slope engineering, 3-dimensional (3D) laser scanning (a.k.a. LiDAR) has been widely implemented to satisfy the desire of resident engineers and contractors for more detailed geotechnical data collected in an efficient manner. Laser scan data produces a very detailed geometric model of the scanning target, typically in the case of slopes for rockfall or slide hazard assessment. Supported by the success of past research using laser scanning for rock slope characterization, this thesis explores the implementation of 3-dimensional laser scanning at the face of an active drill and blast tunnel. Scanning at the tunnel face represents a unique opportunity to document the rockmass before it is obscured by liner installation. The aims of this thesis are manifold:

1) To evaluate whether 3D laser scanning in an active tunnel environment with a static scanner is practical.

2) To identify the challenges in manipulating LiDAR data for geotechnical purposes, especially those specific to data collected in the underground environment.

3) To explore the range of information that can be extracted from laser scan data that is of interest to the contractor/resident engineer.

4) To evaluate the ability to extract geomechanical information from the scan for characterization of the rockmass.

5) To explore the integration of extracted geomechanical data into numerical models which recreate tunnelling conditions based on the reconstruction of the discontinuity network.

1.2 Thesis format

This thesis is written in the manuscript format in accordance with the requirements of the School of Graduate Studies of Queen’s University, Kingston, Canada. The core of the thesis consists of two journal papers which have either been published in or are currently in review for
an international technical journal. Chapter 1 introduces the project and summarizes the objectives. Chapter 2 provides context to the project within the current body of knowledge as well as presenting key concepts and methodologies for the work pursued in Chapters 3 and 4. Chapter 3 investigates the practical deployment of a static LiDAR system in the active tunnel environment and explores the range of operational applications. Chapter 4 focuses on putting to use extracted geomechanical information from the virtual rockmass for numerical modelling. Chapter 5 discusses the implications of the research presented as well as some continuing challenges. Future areas of research and the potential for LiDAR to provide support in engineering design more generally are also discussed in Chapter 5. Chapter 6 summarizes the achievements and contributions of this thesis.

1.3 Synopsis of findings

The research pursued for this thesis is summarized in two sections below. This division mirrors the distribution of research material between the two journal manuscripts included.

1.3.1 Geotechnical applications with a focus on operational applications

A first step towards the practical integration of LiDAR into tunnelling practices was to demonstrate the ability to successfully collect data in a timely fashion at an active tunnel face (Fig 1-1). Following successful field trials, LiDAR data was processed and interpreted. The ability to extract data about tunnel geometry, support and the rockmass were all evaluated. The results from this research have been published in an international journal, Tunnelling and Underground Space Technology (Fekete, S., M. Diederichs and M. Lato, 2010. “Geotechnical and operational applications for 3-dimensional laser scanning in drill and blast tunnels” J. Tunnelling and Underground Space Technology. 25 (5). p. 614-628).
1.3.2 Extending LiDAR-derived rockmass data to numerical modelling

Based on the utility of LiDAR data to extract important rockmass information, the author pursued methods of integrating the data into discontinuum modelling. With an enhanced geostuctural database, the research sought to explore the best approaches for creating representative 3D block models. Examples of block models constructed from LiDAR data to replicate in-tunnel conditions are shown in Figure 1-2 below. The results from this research are presented in journal form, submitted to and in review for the International Journal of Rock Mechanics and Mining Sciences (Fekete, S. & M. Diederichs. 2010. Integration of 3-dimensional laser scanning with discontinuum modelling for stability analysis of tunnels in blocky rockmasses. Int. Rock Mech. 

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1.4 Thesis Summary

The research presented herein aims to explore the various geotechnical applications of LiDAR technology for drill and blast tunnelling projects. The work was motivated by the success of applying LiDAR to rock slope evaluation, but consistently addresses challenges specific to the underground environment. The proposed applications to tunnelling are intended to complement current methods by increasing the quantity and variety of data available, not to replace them. The ability to create sophisticated, highly representative numerical models based on the extracted data is the final aim of the research. With an improved ability to characterize a “virtual rockmass”, representative numerical models can be constructed. As well, this increased ability to characterize
a rockmass fosters a better understanding of tunnel stability. The overarching objective was a practical integration of these methods into current tunnelling operations. The development of a workflow for the integration of LiDAR into geotechnical tunnel evaluation, from data collection to final design output, is the cumulative result of research included in this thesis.
Chapter 2

Project context and important concepts

2.1 Overview of LiDAR technology and practices

3-dimensional laser scanning, commonly termed LiDAR (Light Detection And Ranging), is valuable in that it constructs a highly accurate scene of the scanner’s surroundings. LiDAR is an extension of the technology currently used in total stations, a surveying staple in civil and mining projects. Like a total station, a LiDAR scanner is a range-based imaging tool. The scanner identifies millions of locations in space on the surface of an object or objects, relative to its own position. Each location is assigned a point and together the points form the “point cloud”. The point cloud provides great detail about the geometry of objects within the scanning range. Total station accuracy is the result of repeated sampling of a single point. LiDAR scanners, on the other hand, sample millions of points but each point is only measured once. 3D scanners that re-sample points do exist, but scanning time is increased. LiDAR uses its own light source, typically a laser, to send a signal out which is reflected off an object and recorded by a receiver when it returns. Thus unlike most geophysical methods, LiDAR is not a penetrative technology. LiDAR only documents the physical surfaces that are within its line of sight. The output for each point in the point cloud is a (x,y,z) position in space relative to the scanner, as well as an intensity value (i). The intensity value, which can help visualize data, is indicative of the surface reflectance that is a function of incidence angle, surface roughness and material properties (Lichti and Harvey 2002). Rock surfaces generally have low reflectivity, and contrast between rock types due to coloring is low. There are two primary methods of range detection in laser sensors: Time of Flight
technology (TOF) and phase-offset technology. While they can emit powerful laser pulses that can travel long distances, time of flight scanners require extended data collection time. For this reason, they are not suited to underground work which is highly constrained by the operational schedule and thus this group of scanners will not be discussed further. Phase-offset scanners send out a constant laser pulse but modulate the intensity of the beam. The distance to the target is calculated by assessing the offset in the intensity modulation, which is held in a constant sinusoidal waveform. The offset indicates a two-way travel time, which can be multiplied by the speed of light to obtain a distance or range. Previous research describes in great detail the principles of LiDAR sensors (Lato 2010). Careful calibration of the scanner’s moving parts allow the laser beam to be accurately rotated, collect data in a 3D sphere and place points precisely in space. Spatial resolution of LiDAR is a function of the beam width and angular sample interval (Lichti 2004). The user can usually specify the desired angular sample interval based on the level of detail required. Phase offset scanners can typically collect data from distances of up to 80 m for surfaces with 90% reflectivity. Rock and shotcrete surfaces tend to have reflectivity in the range of 20-40%. The scanner deployed scanned 40 m down a 10 m diameter tunnel length adequately. Before the range of the laser actually became an concern, data coverage had been significantly degraded due to the path of the laser becoming near parallel to the tunnel walls at greater distances. This range is sufficient for most underground applications.

LiDAR scanners may have a static setup, collecting from one stationary location, or may be mobile. Mobile systems include scanners mounted on helicopter, plane or truck bed. Because scanning at the face does not require the scanner to be moved for data collection and stationary scanning eliminates additional positioning error, static systems are recommended for underground applications. In the future as mobile equipment becomes less costly, monitoring of
linear infrastructure may be best pursued with a mobile scanning platform. Underground use of mobile scanning will be limited by the inability to have constant access to Global Positioning System (GPS) data via satellite.

2.1.1 Geological engineering applications for LiDAR

For decades, laser-ranging technology, originally in the form of total stations, has been used to survey large slopes to monitor deformation in both mining and civil engineering projects. Rather than having a total station survey a discrete number of targets on the slope, LiDAR scanning allows for the collection of millions of points quickly, providing much more detailed surveying of the slope. With detailed 3D surveying made possible, researchers looked to new applications including the interpretation of geological models based on physical structure and discontinuity mapping in smaller slopes. The methods of LiDAR-based slope evaluation are the basis for the work pursued in this thesis and thus current state-of-practice techniques and emerging research in this field are described below. The limited extent of current underground applications is also presented.

2.1.2 Rock slope characterization with LiDAR

2.1.2.1 State-of-practice LiDAR applications for slopes

LiDAR scanning of slopes has had various applications including displacement monitoring from great distances (>1 km), virtual outcrop models for geological interpretation (Bellian et al. 2005) as well as discontinuity mapping and hazard assessment (Alba et al. 2005). In the case of Alba et al. (2005) slope models were primarily used to assess the trajectory of rockfall in order to create hazard maps. For others, the primary focus is geological structure (i.e. rock joints) for kinematic assessment of potential rockfall hazard (Kwak et al. 2005). Other
research seeks to extract elements of rockmass character such as joint set spacing or surface roughness which are highlighted in Figure 2-1 (Van Knapen & Slob 2006, Kemeny et al. 2002, Feng & Röshoff 2004). Many have made contributions to developing a workflow for LiDAR applied to slopes, from data collection to integration with existing surveying or slope management systems. For example Kwak et al. (2005) and Hutchinson et al. (2007) discuss the integration of information extracted from LiDAR scans into GIS databases for infrastructure hazard management. The feasibility of LiDAR as a geotechnical data collection tool has been assessed. For example, a comparison of rock slope evaluation methods found that ‘virtual’ joint mapping based on laser scanning was overall less costly than traditional joint mapping with a compass (Slob et al. 2005). While equipment costs increased, the large savings in labour more than compensated.

2.1.2.2 State-of-Art advances for use of LiDAR for slopes

More advanced data manipulation methods and novel slope applications are being investigated. Voyat et al. (2006) use the discontinuity orientation and position to reconstruct block geometry in a slope. From this geometry, models using the limit equilibrium method as well as the discrete element method were run and successfully compared to in situ conditions. Other recent advances in LiDAR data use include Lato et al.’s (2010) assessment of bias due to joint orientation relative to the scanner for slopes. This contribution is significant in that it quantifies the contribution of bias to joint survey results, which had previously been cited as a key challenge (Sturzenegger et al. 2007) but never investigated in greater detail. Lato et al. (2010) propose correction factors relative to slope orientation and instruct how to optimize scanning location based on known joint sets. The effective use of mobile LiDAR data collection for a more efficient evaluation of hazards along linear infrastructure has also been demonstrated (Lato et al.
Mobile LiDAR data collected by airplane, helicopter or truck can be used to more quickly identify potential rockfall source zones or slope geometries that are prone to hazardous rock release. If more detailed mapping is desired, fusion of mobile and static data is possible for better point cloud coverage (Lato et al. 2009). Another state-of-art application for rock slopes is change-detection for rock fall monitoring. This has been demonstrated both by simulating rockfall as well as in progressive release of rock blocks over several years (Donovan & Raza Ali 2008, Lato 2010).

![Figure 2-1: Elements of rockmass classification, many of which can be described by analyzing LiDAR data (Black outline indicates that the element can be well described, grey outline indicates that it can be characterized, though not directly calculated, and grey dashed outline indicates that some assessment can be made potentially triggering further investigation) (After Hutchinson and Diederichs 1996).](image-url)
2.1.3 Current applications of underground LiDAR data

While the development of methods for the collection and analysis of laser scan data for
slope engineering has been extensive, there has been a very limited amount of research for
underground applications. This is likely due to the fact that until recently, scanners were not well
suited to the underground environment. Developments (including increased robustness, increased
portability and reduced scanning time to minimize interruption of construction schedule) now
allow for the practical use of laser scanning underground. State of practice for most tunnel
operations is to use a laser profiler for documenting excavation geometry, see Figure 2-2. These
typically collect helical data sets with 10 cm longitudinal spacing between profiles and do not
offer continuous surface data. Some forward-thinking contractors have implemented the use of
laser scanners to document final rock or liner geometry on completed tunnel sections for
monitoring purposes. Even rarer are the tunnelling projects that have required tunnel heading
documentation by LiDAR for verification of contract requirements, including the Devil’s Slide
tunnels (Decker 2008). Trials to track tunnel deformation with LiDAR have been pursued, where
scans of the same tunnel section, collected at intervals over a period of time, are quantitatively
structure mapping has been conducted with varying success, often using propriety software (Mah
2.1.4 Comparison with photogrammetric methods

LiDAR data collection has often been compared to photogrammetry because the two methods share many of the same applications and produce point cloud datasets. However, the methods vary in field data collection and the data produced. Each has their respective strengths and weaknesses. For example, photogrammetry simply requires a camera, obtainable at a much lower cost than a LiDAR scanning system. As well, camera calibration is a more transparent process and is conducted by the user, in contrast to the “black-box” calibration which LiDAR manufacturers conduct within the confines of their laboratories (Habib 2009). Photogrammetric methods have been in use for longer than LiDAR for slope hazard assessment. As a result, many of the geotechnical assessment methods that are now being used with LiDAR data, originated from analysis of photogrammetric point clouds. In addition, there has been sufficient time for photogrammetry software specific to geotechnical applications to be developed. There are
examples of photogrammetry, coupled with targeted software, which has been fully integrated into rock slope remediation, including the evaluation of rock structure and identification of zones for support (Haneberg et al. 2006). Successful underground geotechnical assessment with photogrammetry has been discussed by Birch (2008) and Gaich & Potsch (2008). They have demonstrated the capability for creating aligned underground surface models, mapping geological structure, measuring shotcrete thickness, extracting cross-sections and extracting joint surface profiles in ADAM technology’s 3DM analyst and 3G ‘s JointMetriX3D respectively.

However, photogrammetry is less suited to underground use than LiDAR because it relies on external illumination of the target (a lighting system) and data can suffer when shadows occur. Furthermore, each location in a point cloud obtained from photogrammetry must be seen from at least two camera positions. This is highly undesirable in the case of high relief rock surfaces (blocky ground) because many locations on the rock surface will not be visible from two vantage points and therefore will not be documented. Thus because of the improved ability to document the rockmass without the need for additional lighting, the author puts forward LiDAR as the more promising technology for underground rockmass characterization.

2.2 Field trials sites

Field trials were conducted at two active tunnel project sites, and at two completed, unlined tunnel sites. All tunnels are in the Oslo region of southeast Norway and access to them was the result of collaboration with the Norwegian Geotechnical Institute (NGI). The site locations are illustrated in Figure 2-3 below.

Of the two unlined tunnel sites, the first is NGI’s Bånkall test tunnel, a 60 m long, 6 m diameter testing facility (Fig. 2-4). This site was used to test scanning procedures before proceeding into the operational tunnel environment. The geometry of the tunnel walls is mostly a
function of blasting. As a result, this site was not very useful for assessing geologic structure and creating numerical models specific to blocky rockmass. However, some large joint surfaces present in the tunnel sidewalls were used in joint surface/roughness work (Fig. 2-5).

The other unlined tunnels are located below the Akershus fortress in downtown Oslo and date back to 1905 when they were constructed for the railway. The two tunnels, now abandoned, are 4.5 m in diameter, 88 m and 30 m in length. This site was used to test laser scanning in a different geological structure style. The rockmass was very blocky, with many different joint orientations and tightly spaced joints (Fig. 2-6).

The field sites that provided access to an active tunnel construction environment are in the Bærum municipality, to the west of Oslo. Data collection took place at two project sites in close proximity, both a part of the Sandvika-Asker railway expansion project. The Bærums Tunnel was surveyed from the Sandvika project site and Haslum tunnel from the Skallum project site. Between the two sites a total of 5 headings were documented. The two sites fall in the same geological setting, tilted Paleozoic sedimentary rock. Borehole drilling shows that intact rock can be very massive with sections of core, up to 2 m in length, having 100% recovery and no fractures. The three headings at the Sandvika site included two 10 m diameter tunnels and one 15 m tunnel. The Skallum site had two 10 m diameter tunnels. These were drill and blast operations, typically with 5 m blast rounds for the 10 m diameter headings. These tunnels were supported with pattern bolting (2 x 2 m spacing, 2.4 m long bolts) as well as 10 cm of steel fibre-reinforced shotcrete. A completed tunnel section is shown in Figure 2-7.
Figure 2-3: Location of tunnel field sites, Oslo, Norway (Google 2010)
Figure 2-4: Bånkall test tunnel in quartz-bearing syenite northeast of Oslo

Figure 2-5: A large joint surface in Bånkall test tunnel used in detailed surface analysis.
Figure 2-6: One of the Akershus Fortress tunnels in downtown Oslo, Norway (30 m in length).

Figure 2-7: View down completed tunnel section (10 m diameter), Sandvika tunnel site.
2.3 Geologic context of field sites

The Oslo region of southeast Norway has complex geology with units of all three major rock types, varying in age from Precambrian to Permian. The area has generally been termed the Oslo Graben. The graben itself, about 200 km long and 30-70 km wide, formed by block faulting during a period of rifting with increased volcanic activity (late Carboniferous through to the Permian) (Ramberg et al. 2008, Oftedahl 1960). The graben, which preserves Paleozoic sedimentary units and contains Permian volcanics, is surrounded by Precambrian basement (Fig 2-8). The basement rock is largely high grade metamorphic rock and heavily deformed. The igneous units include large intrusive bodies as well as lavas, related to the Permian rifting system. The sedimentary units are Cambrian-Silurian in age and formed in shallow seas. The sedimentary units were deformed after deposition most likely during the Late Devonian (Størmer 1966). The source of deformation is the Caledonian orogeny, the product of Baltica and Laurentia colliding hundreds of kilometers to the west of Oslo (Oftedahl 1960). On the mesoscale, this compression resulted in zones where bedding is tilted or folded (Fig. 2-9 B,C). At the map scale, the sedimentary units have been displaced in a complex décollement and splay thrust system (Bockelie 1982). A geological map of the Oslo area is found below in Figure 2-8. For simplification, geological units in the legend are divided broadly into Precambrian metamorphic, Cambrian-Silurian sedimentary units and Permian volcanics (which is an appropriate generalization in the Oslo region). Note: The Akershus site appears to be in Cambrian-Silurian sediments. This is because at surface there are sedimentary units. The tunnels investigated, however, pass below the contact of the sedimentary units through Precambrian basement.
Figure 2-8: Geology of the Oslo region (NGU 2010) Note: field sites are indicated with black bounded triangles.
The following descriptions of geology, specific to each tunnel site, are based on site observation, field samples and confirmed by bedrock geology maps available from the Geological Survey of Norway (NGU). Field trip excursion guidebooks from past conferences were also helpful for providing specific geological context.

The Bærum and Haslum tunnels are excavated in an area of Cambrian-Silurian sediments. The sedimentary units vary in composition, but include shales, sandstone and limestone in varying ratios. At the Sandvika and Skallum project sites, shales and lime mudstones were most common. The sections of tunnel documented by laser scanning are in rock that is Late Ordovician to Early Silurian in age, based on the knowledge of tunnel geologists, maps of the Oslo region (NGU 2010, Holtedahl & Dons 1966) and by comparison with descriptions of other outcrops in the Sandvika area (Skjeseth & Hagemann 1960). Local experience of Ordovician units finds that the lithology is gradational with varying compositions between shale and limestone, with limestone commonly occurring in layers (Henningsmoen & Spjeldnaes 1960). This description is consistent with samples collected from the site which contain some lime but are primarily silica-mud-based. The sedimentary structures, exposed in wirecut outcrops near the tunnel exit portal, are also consistent with this description, see Figure 2-9 A. Centimeter to decimeter thick lime-rich layers occur within the more prominent shaley layers. The lime-rich layers often appear as lenses and occasionally as decimeter-sized nodules. These sediments were deposited in a shallow marine environment, generally well ventilated though interlayers of black shale indicate intermittent periods of deeper, stagnant conditions (Henningsmoen & Spjeldnaes 1960). The sedimentary bedding has been tilted to approximately 60°, as seen in the tunnel face at the Sandvika site (Fig. 2-10). Narrow mafic dykes (likely diabase), up to 3 m across, are visible in rock cuts, see Figure 2-9 A. These dykes are associated with Permian rifting and are present...
throughout the Oslo area (Skjeseth & Hagemann 1960). Narrow calcite veins (1-2 cm), of unknown age, occasionally cross-cut the sedimentary layers.

The Bånkall tunnel is in massive plutonic rock, Permian in age. This intrusion is one of many large batholiths that formed in the Oslo area approximately 270-250 ma following rifting (Ramberg et al. 2008). The tunnel is excavated in quartz-bearing syenite with grey plagioclase (Holtedahl & Dons 1966) with a characteristic pink color (Fig. 2-11). In this region, syenitic rocks of this composition are generally termed “nordmarkites” (Ramberg et al. 2008). The unit is generally very coarse-grained and in zones porphyritic. This particular composition is termed “syenite of Grefsen type” (Oftedahl 1966).

The Akershus Fortress tunnels are located in a horst of Precambrian bedrock. The large outcrop below the Fortress is described as one of the most geologically interesting sites in the city of Oslo (Henningsmoen 1966) and many geology students visit it each year, earning it a title that translates to “Student Mountain” (Dons et al. 1996). There are a few faults at the site, making it possible to observe several geologic units. A fault has uplifted a section of basement rock and offsets the younger sedimentary units above. Cambrian conglomerate and arkose sandstone units are visible above the Precambrian gneisses, across a discontinuity that represents approximately 500 million years (Henningsmoen 1966, Dons et al. 1996). At the north end of the outcrop, these sediments are overlain with black shale and Permian Sills (Henningsmoen 1966). However, the zone through which the two tunnels pass is to the south of the discontinuity and the tunnels lie only in Precambrian gneisses (Fig. 2-12). At this site, the metamorphic unit is primarily amphibolite gneiss with some felsic pegmatite zones (Dons et al. 1996).
Figure 2-9: Wirecut outcrops featuring Cambrian-Silurian interbedded sedimentary unit at Sandvika portal site. (A) Permian dyke intrusion through thinly bedded shale-limestone, some lime nodules are visible. (B) Fold in sedimentary layers. (C) Tilted bedding across tunnel exit profile, facing east.
Figure 2-10: Tilted sedimentary unit in the face of active tunnel, Sandvika site, facing west.

Figure 2-11: Bånkall test tunnel in massive quartz-bearing syenite, “nordmarkite”.
2.4 Overview of LiDAR data collection

While the data collection procedures described in this thesis are discussed in the tunnelling context, they are equally applicable to mining projects and civil excavations of varying geometry. The choice to focus on tunnels was based primarily on access to active tunnelling sites for field trials. Field trials were conducted with a static LiDAR tripod setup. The field research team initially brought a field laptop to ensure that scan data was consistently retrieved and of good quality. However, in later trials, having had no data collection difficulties, data was simply recorded to the scanner hard drive and transferred to a desktop for processing after returning to the office. This significantly reduced total data collection time. A more detailed discussion of scanning practice at the face, including scanner specifications is included in Section 3.3.2.
For future streamlining of data collection, the author recommends mounting the scanner on an all-terrain vehicle (ATV) or another vehicle so that the equipment does not need to be carried to the heading for each excavation round and can reach the face more quickly when the heading is ready for scanning. Once at the face, the equipment would be parked and the scan conducted from a static survey position. Some proposals have been made to mount the scanner on a jumbo boom or shotcreting equipment as has been done with laser profilers, recall Figure 2-2. However, the author recommends caution in this pursuit due the unknown effect of machine vibration during data collection. Furthermore, scanners may be increasingly robust, but the system’s costly calibration and even more costly components could be compromised by the vibration and jolting movements of tunnelling equipment. As well, in a multi-heading project, this method of mounting would limit the number of headings that the scanner can access if drilling/shotcreting equipment is not common to all headings.

At active headings, only one scan was required per blast round. However for the completed unlined tunnels at Bånkall test facility and Akershus fortress tunnels, multiple scans were performed in order to create full tunnel models. In narrow tunnels, the rock wall becomes oblique to the scanner line of sight within a short distance. The surface obliqueness greatly decreases the ability to interpret the point cloud (Lato et al. 2010). In other words, the closer the scanned surface is to perpendicular with the laser path the better. It was found during field trials and subsequent processing that sections scanned where the rock surface and laser formed an angle of 45°-90° had sufficient coverage (Fig. 2-13). Thus, in order to ensure that all tunnel sections obtained this coverage, scans had to be performed at much shorter intervals along the narrower tunnel in order to have acceptable data coverage. This coverage is critical if rockmass characterization is to be conducted, and even when it is not, aligning the scans becomes easier.
when there is more redundant data between scans. Thus, the disadvantage of scanning small-diameter unlined tunnels is that more time is required for data collection and more data must be managed later on. Based on the work at the Bånkall and Akershus tunnels, it was found that a one diameter interval between scans optimized overlap and data redundancy. At a one diameter scanning interval, all tunnel sections fell within this $> 45^\circ$ obliqueness zone in at least one scan, with the tunnel coverage outside this zone still remaining adequate for scan alignment. This coverage issue and need for additional scan locations in smaller diameter tunnels are illustrated in Figure 2-13.

Figure 2-13: Scan positions and scan coverage for two tunnels of differing diameter in plan view. Zones in grey are well captured by one scanner, because the tunnel wall obliqueness is within an acceptable range (angle between scanner line of sight and surface is $>45^\circ$). The narrower tunnel requires additional scan locations for adequate coverage.
2.5 Data processing and overview of software use

This section provides an overview of data processing required for the results presented in Chapters 3 and 4, including the processing of point cloud data for feature extraction as well as for constructing 3D discrete element models.

2.5.1 LiDAR data processing and software

Once LiDAR data has been collected, several steps are required prior to being able to extract geotechnical information. The reduction of data to a practical size is required to handle the demanding processing needs of very large datasets (up to GBs in size). The author consistently converted point clouds to a surface mesh, though it is not necessarily required. While this method is computationally demanding and requires additional processing effort, the author found that discontinuities are far easier to identify and interpret from a continuous, interpolated surface than from discrete points in space. The steps required to create the tunnel model for interpretation are discussed in more detail in Section 3.4. For the purpose of this thesis, PolyWorks (InnovMetric 2009) was the primary software used for manipulation of point cloud data. This selection was made based on the ability of the software to handle large data sets and successfully create meshed surface models at the level of detail required. This selection was made despite the fact that the program is targeted to other industries and simple geotechnical evaluations can be onerous. Due to incompatibility of proprietary file formats, point intensity values could not be loaded into PolyWorks. For this reason Leica’s Cyclone (2009) was used to visualize the raw point cloud with intensity contrasts. Cyclone has similar functionality to PolyWorks for data visualization but has a reduced ability to mesh and perform calculations on the data.

There has been some evaluation of automated joint selection algorithms for rock slopes in the literature (Slob et al. 2005, Van Knapen & Slob 2006). The successful use of automated joint
identification with Split-FX (Split Engineering 2008) has, however, been limited to rock slopes with large joint planes and distinct structure. In underground rock exposures, fracture planes are not necessarily natural rock structure because of damage due to blasting, scaling, road headers etc. Joint identification algorithms have difficulty differentiating between induced and natural fracturing. The author invested significant effort to try to extract meaningful results from structural data obtained from automated joint identification in Split-FX from either the crown or tunnel face. Even after testing a significant range of patching parameters, automated joint selection failed to produce any useful joint characterization. Results were highly dependent on automation parameters. Results were consistently too noisy when values were not restrictive enough or provided meager structural information when values were limiting. As a result, for the work presented in this thesis, joint selection was performed interactively. In interactive joint selection, the boundaries of each joint plane are manually selected. Points falling within this zone are used to compute a best fit plane, whose location and normal vector information can be used in further analysis.

Underground LiDAR data sets are challenging because they can be very large in size but also require meshing algorithms that can handle “fully 3D” data rather than “2.5D”. (Note: 2.5 D data have points positioned in (x,y,z) space but do not allow two points to have the same z coordinate, while fully 3D data allows this (where z is the vertical coordinate). Thus a tunnel scan is a fully 3D dataset because a position on the tunnel floor and tunnel crown may have the same x,y coordinates and different z coordinates.) The challenge of fully 3D data will be further addressed in Section 5.3.2. However, in the context of data extraction, these challenges require current geotechnical calculations to often be conducted external to the point cloud software. For example, joint spacing calculations for the presented work were completed in Excel (Microsoft
Office 2007) for ease of calculation, using plane normal direction and plane centroid. In order to increase the efficiency of such a process, macros may be written and integrated into existing point cloud software processes.

2.5.2 3DEC methodology and input parameters

In order to adequately model deformation in blocky ground and model discrete features in 3D space, the 3-dimensional discrete element method (DEM) was used. DEM is a type of discontinuum modelling where nodes of blocks are allowed to move, disconnect etc., rather than being linked together as is the case in the finite element method. For the purpose of this research, Itasca’s 3DEC software package (2004) was used due to flexibility and computing capabilities. By replicating the geometry of geological discontinuities, introducing a tunnel excavation and applying the appropriate stress regime, the stability of the excavation can be assessed. Several modelling decisions were made in order to ensure consistent results within a practical time frame. Rather than try to replicate geological conditions of the field trial site exactly, the focus was placed on whether or not recreating observed block failure in tunnels is practical based on data extracted from a LiDAR scan. More precise calibration to site conditions requires additional data that was not available, such as the field stress regime. This calibration is necessary if stability modelling is to be integrated into site engineering or back-analysis, as the author proposes for future work.

One significant assumption of the models presented in this thesis is that the rock blocks perform rigidly (i.e. the blocks themselves do not deform). This assumption is typically acceptable for blocky rockmasses where deformation is the result of displacement of blocks along discontinuities. This modelling decision greatly reduces computational requirements. Deformable blocks require zoning (an additional computational step) and each zone is allowed to deform
based on assigned strength parameters during each calculation step, which greatly increases computation time even with simple models. Given that the constructed models typically consisted of tens of thousands of blocks, the computational demands of deformable blocks would have either surpassed processor capabilities or calculations would have taken an impractically long time. Selecting rigid blocks would not be justifiable if the tunnel was under high stress conditions or the rock material itself was weak and deformed plastically. Neither of these were the case for the tunnels where field trials were conducted.

Field stress values for the site were not available and therefore the presented models use the simplest field stress regime, isostatic. The equivalent overburden stress for 25 m of rock is used to calculate the initial field stress on all blocks in 3 directions. A depth of 25 m was selected to simulate the behavior of a shallow tunnel which was appropriate for the case-study tunnel site as well as staying in line with the assumptions of a rigid block model. The entire rockmass model was constrained by 6 rectangular prisms to ensure that blocks could not move outside the model boundaries.

To ensure proper model geometry, a low cut length tolerance (“atol”) had to be assigned to ensure that even small block faces were allowed to form. This was especially required in the deterministic model where many joint cuts were concentrated around the tunnel opening. Additional details about how the models were constructed, regarding the interpretation of structural data etc. can be found in Chapter 4. The code used to build models and record displaced blocks in the stability analysis are included in Appendix A.
Chapter 3

Geotechnical and operational applications for 3-dimensional laser scanning in drill and blast tunnels

3.1 Abstract

3-dimensional laser scanning (LiDAR) techniques have been applied to a range of industries while their application to the geological environment still requires development. LiDAR is a range-based imaging technique which collects a very accurate, high resolution 3-dimensional image of its surroundings. While the use of LiDAR in underground environments has been primarily limited to as-built design verification in the past, there is great value in the scan data collected as the excavation advances. The advantages of employing a static LiDAR system for geotechnical and operational applications have been demonstrated at a drill and blast tunnel operation at the Sandvika-Asker Railway Project near Oslo, Norway as well as in two other test tunnels in Oslo. The increased scanning rate of newer systems makes it possible to remotely obtain detailed rockmass and excavation information without costly delays or disruption of the construction workflow with a simple tripod setup. Tunnels are non-traditional environments for laser scanners and add limitations to the scanning process as well as the in-office interpretation process; these are discussed. Operational applications of the data include:

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calculation of shotcrete thickness, as-built bolt spacing, and regions of potential leakage. The authors find that LiDAR data, when correctly interpreted, can also provide detailed 3-dimensional characterization of the rockmass. Geometrical characterization of discontinuity surfaces, including location, orientation, frequency and large-scale roughness, can be obtained. Discontinuity information may be synthesized for a much more representative geomechanical understanding of the rockmass than was previously possible with traditional hand mapping limited by face accessibility. The alignment of LiDAR scans from successive exposed faces offers additional interpretation and recording advantages, particularly where shotcrete is subsequently applied behind the face. In aligning scans, larger scale features can be readily identified and rockmass trends over several rounds may be identified. Discontinuity geometries and characteristics may be input into kinematic and numerical models for further analysis.

Keywords: laser scanning, LiDAR, remote sensing, rockmass classification, structural evaluation, tunnel

3.2 Introduction

Applications of laser imaging span many industries including architecture, crime scene investigation, art preservation, transportation infrastructure maintenance, open pit mining and geo-hazard mitigation. In terrestrial applications, both mobile and static systems can be employed. Developing applications of mobile technology include urban planning and railway hazard monitoring. Static systems have traditionally been employed for parts manufacturing inspection and chemical plant design and maintenance. The geological engineering community utilizes laser imaging for landslide monitoring and more recently, rock outcrop characterization, rockfall hazard assessment and stratigraphy modelling (Bitelli et al. 2004, Kemeny et al. 2006, Strouth and Eberhardt 2005, Buckley et al. 2008).
The application of laser scanning in underground excavations has been increasing in recent years. Low density profiling scanners, often referred to as profilers, have been in use for more than a decade. Advantages of the profiling scanners are their ability to scan long tunnel sections very quickly. Such scanners have been deployed in completed tunnels at up to 120 km/hr providing a helical data set (Fröhlich & Mettenleiter 2004). A construction control scan with this equipment would typically involve scanning at approximately 300 rotations per second and approximately 2000 points per section profile with a decimeter between profiles (Fröhlich & Mettenleiter 2004). While these profiling systems are appropriate for producing efficient 3-dimensional as-built models for construction and contracting calculations (overbreak, shotcrete control and tunnel alignment), a lot of key geotechnical information is not available and can only be obtained in higher-resolution scanning.

To date, the primary application of 3-dimensional laser scanning in tunnelling has been the creation of as-built final lining models. For example, an as-built model to monitor seepage of a 5.6 km section of the Dallas Area Rapid Transit tunnel system was created from a static LiDAR scanning system (Jackson 2008). There have also been examples of LiDAR used to evaluate rock or liner deformation in tunnels (Van Gosliga et al. 2006, Lemy et al. 2006). Figure 3-1 below shows three scenes from a scan data set taken at the competed intersection of 3 headings near Oslo, Norway, one section of the Asker-Sandvika Railway Project. The top-left and bottom scenes are viewed from ‘inside’ the data, the top-right scene is seen obliquely from above i.e. from ‘within’ the rockmass. Features that are easily identifiable include shotcrete lining, ventilation, and final excavation geometry.
Figure 3-1: Three scenes of a LiDAR data set from the completed intersection of the 3 headings at Sandvika tunnel site. Point data is decimated in this view.

There remains a lot of unexplored potential for data collected during the active construction phase. With limited time allocated to engineering characterization during construction, tunnel design engineers must identify specific technologies that provide the most practical information for design while minimizing disruption to the excavation workflow. Given recent advancements in the rate of data collection, phase-based laser scanners are practical additions to the excavation cycle. The employment of a static LiDAR scanner for geotechnical assessment in a drill and blast tunnel operation has been demonstrated in a collaborative project involving Queen’s University (Kingston, Ontario) and Norwegian Geotechnical Institute (Oslo).
Four tunnel sites near Oslo, Norway have been used, including two active construction headings in the Asker-Sandvika Railway Project and two completed unlined rock tunnels. This paper will explore the procedure of scanning in tunnels with a static system, its challenges, limitations and adaptive solutions. Further, the technical applications will be illustrated, both relevant to the contractor and geological engineers, as seen in Table 1.

**Table 1 Applications of LiDAR in tunnelling**

<table>
<thead>
<tr>
<th>Who's interested</th>
<th>Contractor/Tunnel engineer</th>
<th>Geological engineer/Geologist</th>
</tr>
</thead>
</table>
| **Applications** | • As-Built tunnel model  
○ Final liner surface model  
○ Final rock surface model  
• High density rock/tunnel profiles  
• Support installation quality control  
○ Contoured shotcrete thickness model  
○ As-built bolt spacing  
• Potential leakage location mapping  
| • Structural discontinuity geometry  
• Joint spacing  
• Joint surface characterization  
• Structural overbreak analysis  
• Wedge identification  
• Linear feature mapping across faces  
• Geological texture geometry |

**3.3 HD laser scanning technology and tunnelling**

**3.3.1 Tunnel specific challenges and technological solutions**

The active tunnelling environment is more demanding and challenging than those where LiDAR scanning has traditionally been employed. Tunnels require robust systems that are effective in dusty, damp, and dark conditions. One key strength of LiDAR scanners is that they can function without underground lighting because the laser acts as its own "light source". In the past, the use of LiDAR in active tunnels has been impractical due to long scanning times for “time-of-flight” systems (based on return travel time of beam). However, the development of
portable, high-speed phase-based scanners now allows for their use in active tunnels. Phase-based (or phase offset) scanners emit a continuous wave with modulated amplitude (AMCW) that varies according to a sinusoidal function (Thiel & Wehr 2004). The difference in phase between the transmitted and returned wave is used to calculate the distance to the target. Because of the AMCW source, the rate of data collection of phase-based scanners (over a million points per second) can be 1-3 orders of magnitude greater than standard time-of-flight systems. The trade-off for increased acquisition speed is that the range of phase-based scanners is limited to 80 m. This range is nevertheless sufficient for most underground environments including infrastructure tunnels which are the focus of this paper.

3.3.2 Data collection in an operational environment

Laser scanning data collection becomes highly constrained by construction workflow in an active tunnel environment. The authors used a stationary tripod setup at Sandvika and Skallum project sites to scan the face, walls & crown after successive rounds. During this demonstration phase, five separate headings (four 10 m diameter and one 15 m diameter) were scanned for multiple face positions. The tunnel faces were scanned in rotation according to the excavation schedule. The scans were conducted after blasting, mechanical scaling, and manual scaling. The scanning was initiated within 5 minutes of mechanical scaling with little time for dust dispersal. Nevertheless, there was minimal apparent degradation of scan quality due to dust although care must be taken at all times to protect exposed system moving parts from dust and moisture (new hardened systems are now available). The rigorous mechanical scaling did cause damage to the blasted rock surface and it was noted in the field that some structural features were obscured by the scaling marks. The ability to identify rock mass discontinuities is improved if scanning is performed before mechanical scaling; the trade-off is that pre-scale data underestimates the actual
shotcrete thickness. The authors favored the ability to perform both liner thickness quality control as well as geotechnical assessment and therefore chose to scan post-scaling. This time frame was also favorable for the contractor as it corresponded with the time allotted for geotechnical engineering assessment.

With this setup, the full process was found to be easily accomplished by one person although an additional person can provide support for equipment transport as well as providing a safety guard for the scan operator, typically standing or sitting in the centre of an active heading. The scanner was set up just inside the limit of supported rock, for safety and best scanning practice, approximately 7 m from the faces (10 and 15 m span), ideally 0.5 to 1 diameter from the face is the optimal position. Figure 3-2 includes photographs for one heading at the Sandvika site showing the quad-boom drilling equipment as well as the LiDAR tripod setup at the face. The product of each LiDAR scan is a 3-dimensional "point cloud", in an x,y,z coordinate system relative to the scanner. As well as position, each data point is assigned an intensity value and a normal vector. The intensity value, i.e. strength of returned beam, aids in visualization and characterization, while the normal vector helps in creating surface models of the data. The “normal vector” points away from the scanned surface toward the scanner, parallel to the beam path. This normal vector allows the point cloud software to assign a “front” and “back” face to the point and aids with meshing.
Figure 3-2: (A) Quad-boom Jumbo at Sandvika railway tunnel, near Oslo (B) LiDAR tripod set up at 10 m diameter face (C) Detailed view of tripod set-up with field laptop.
The data for this research was collected with the Leica Geosystems HDS6000, a phase-based scanner with a maximum range of 80 m at 90% reflectivity (less for rock surfaces). The scanner has a 360° horizontal field of view and a 310° vertical field of view, scanning all but underneath the legs of the tripod setup. The system provides high speed, high density acquisition at 500,000 points per second. The scanner offers the choice of different resolutions with point clouds ranging from hundreds of thousands of points to tens of millions for a single scan. The tradeoff of high point density is extended scanning times and increased computer processing hardware requirements. When set up 7 m from the face at the Sandvika tunnel, the selected resolution setting produced 6 mm intervals between points on the face. The system has a calibrated positional accuracy (horizontal and vertical) of 1.5 mm and a range noise of 1.25 mm rms at 25 m distance (Calibration results, Z +F USA Inc, 2008). At this high resolution setting, scanning at the tunnel face requires 3 minutes with an additional 2 minutes to download to a field computer (not required for scanners with internal memory). The entire set up, scanning and take down processes were completed in under 7 minutes for each round, including download which is can be omitted in the field if desired. In this way, excavation work flow was not interrupted as the scanning could be easily fit into the 30 minute time slot provided for geotechnical assessment.

3.3.3 Limitations of tunnel scanning

The primary limitations of 3-dimensional laser scanning from a single setup position (per face) are occlusion and scan bias. Occlusion, often referred to as "shadowing", limits data acquisition to what the laser can ‘see’. Because the ‘view’ of some joints may be limited or fully obstructed, these will not be documented by the scan (Lato et al. 2010). Sturzenegger et al. (2007) found that a roadside rock outcrop cannot be fully sampled from one scanning location in the comparative stereonet analysis of two scanning locations and that the best coverage is, in
principle, achieved with multiple scans in both the vertical and horizontal planes. However, in an operational tunnel environment, time and space limitations may only allow for one scan per round. This may limit the reliability of data to detect discrete structures with unfavourable “viewing” angles. However, the tunnel environment provides for a wide range of viewing angles (joint orientation relative to scanner) so that occlusion is reduced for overall rockmass characterization purposes. At the Sandvika site, the primary source of occlusion (with the tripod-mounted scanner) was a shallowly dipping joint set when it occurred in the upper face. If this joint set was deemed critical in stability analysis, its visibility in the lower face would allow for extrapolation into the upper portion of the face. Mounting the scanner on the scaling or drilling boom has been considered in order to reduce vertical occlusion and minimize set up time, although the scanning system would require additional hardening for this application.

Bias is a significant limitation in geotechnical assessment as documented by Terzaghi (1965) with respect to scanline and drill hole orientation. Influences of additional scanning bias have been widely documented for rock slopes (Sturzenegger et al. 2007, Lato et al. 2009) especially with regard to the ‘invisibility’ of discontinuities parallel to the line of sight. However, LiDAR scanning in tunnels is somewhat less susceptible to the bias observed when scanning rock slopes. In a rectangular tunnel heading, for example, three roughly orthogonal planes are scanned (walls, face and crown). Thus, a surface near-parallel to the laser in the face may be visible in the crown or walls and vice versa. Due to bias the scanner may not ‘see’ every discontinuity but as long as it is part of a set that repeats, it will be detected on at least one of the scanned surfaces. It is therefore important that in selecting a tripod position, operators are aware of and note any critical discrete structural features that may not be visible in the scan. This fact
again reinforces that the experience and judgment of the data collector may contribute to the quality of laser scanning results.

### 3.4 Data processing

While the point cloud collected contains accurate geometric information, the data set still requires some processing in order to a) reduce the size of the data set to a manageable size b) create continuous surface models (rather than just points) and c) align the data with adjacent scans. Once this processing has been completed, the data can be used for analysis. Not all types of analysis or data sets require all these steps but generally, this is the work flow. LiDAR data sets can be up to GB’s in size and so in order to manipulate the data in an efficient manner, even with a powerful computing station, the data set should be reduced to the region of interest (ROI). Any unwanted objects can be deleted: scaling equipment, muck piles, reflections etc. In addition, depending on the level of precision required and the analyses to be conducted, the processor may elect to decimate the data, in other words, to use only 1/4 or 1/16 points collected. If there are specific zones of interest identified in the decimated data set, a smaller region with higher point density may be subsequently analyzed in detail. The creation of the mesh or surface model is an important step in both handling the large data sets as well as in preparation for analysis. This process reduces the size of the data by assigning groups of adjacent points appearing to lie on the same plane to triangles with a definite centroid, area, vertices and normal vector. The mesh often improves the interpreter's ability to visualize the data and is necessary for any analysis requiring continuous surface information. The process (Figure 3-3) of reducing the point cloud (A) to a mesh (B) in order to create a 3-dimensional tunnel model (C) provides for improved visualization, data reduction and the ability to perform geometrical investigations (Fig. 3-3D) such as the analysis of overbreak or final profile compared to a design profile.
Figure 3-3: Processing (A) Raw point cloud (B) Triangular mesh, and (C) Meshed tunnel model, Sandvika site. (D) Radial difference map showing final shotcrete profile compared to a cylindrical design profile (contoured on the rock-shotcrete model or on the cylinder as desired).

An alignment (registration) step is required in order to connect scans and create full tunnel models. The alignment of the rock surfaces of 3 rounds at the Sandvika site (i.e. the shotcrete liner etc. has been edited out) is shown in Figure 3-4. This can be done using relative position markers (visible bolts, pipes, etc appearing in consecutive scans) for “rough” alignment or can be tied into absolute positioning using a total station. Data point spacing on the tunnel wall
increases with decreasing wall-beam angle and data overlap between scans increases reliability and alignment accuracy as discussed in Section 2.4. For scans of existing tunnels, it is recommended to use a longitudinal scanning spacing (distance between tripod setups) of between 1 and 2 tunnel radii. The final tunnel model of the Bånkall Test tunnel, illustrated in Figure 3-5A, is assembled from 11 aligned scans. A view from inside the tunnel from a photograph as well as from within the LiDAR point cloud highlighting roof and wall structure are also included (B,C).

Various software programs can be used to view, align and model point cloud data. For this project, Cyclone (Leica Geosystems) and PolyWorks (InnovMetric Software Inc.) were used. The ability to analyze and interpret the data is a function of data quality, program functionality and also computing power. The large file sizes have high memory requirements for visualization and processing. Further, high-end video cards are essential in order to be able to visualize the data at a practical rate.
Figure 3-5: (A) Complete LiDAR model of 8 m x 60 m Bånkall Test Tunnel: 11 aligned scans, med. resolution, (B) Photograph of LiDAR system with viewpoint A in aligned scans (C) View from 'within' LiDAR model at X (only raw points shown).
3.5 Operational applications

As seen with current applications of laser profilers, the point cloud data of lined tunnel sections have great value for contractors. As already shown in Figure 3-3, final profiles can be compared with design profiles for contractual verification. Furthermore, by aligning face scans obtained with a 3-dimensional laser scanner, a high density model can be obtained which unites information from before and after support installation. This equates to a powerful quality control tool.

3.5.1 Support evaluation and scaling assessment

Similar to the data collected by tunnel profilers, LiDAR scan data can be used to produce rock and final lining profiles. A 15 m tunnel section from the Sandvika site is shown longitudinally and in cross-section in Figure 3-6. These profiles can be easily exported for further use in CAD programs for comparison against original design. After an advance, the tunnel surface has been scanned twice (pre- and post-shotcreting). This allows direct comparison and evaluation of shotcrete thickness in detailed profile or contoured on the whole tunnel model for visualization.

In addition to liner evaluation, the LiDAR data sets can be used to evaluate construction cycle efficiency (blasting, scaling etc) by analyzing the resulting rock surfaces. A 10 m heading at the Sandvika site was scanned after blasting, pre-scaling, as well as after mechanical scaling. These models were then compared in order to evaluate the amount of rock removed by the scaling process. The two aligned pre- and post-scaling models are shown in Figure 3-7A. The cross section highlights a section of significant rock removal with overall scaling depths contoured in Figure 3-7B.
Figure 3-6: (A) Rock and (B) shotcrete LiDAR models of three aligned 5 m rounds, Sandvika site, (C) longitudinal and profile cross section showing detailed comparison of profiles with liner thickness; (D) Shotcrete thickness contoured onto model (with unsupported heading toward the right).
Figure 3-7: (A) Two aligned tunnel scans (view from “behind” face), pre- and post-mechanical scaling with a cross-section A-A’ showing profile where scaling has removed material. (B) Quantitative comparison of pre- and post-scaling scans, where hot colors indicate areas where material has been removed in the process (oblique view).

Quality control of support can also include bolt installation. The re-evaluation of bolt positioning can be conducted very efficiently in data visualization programs in order to obtain as-built bolt spacing and audit bolt density. Figure 3-8 shows metal plate anchored bolts at the Sandvika site, their spacing, and an estimate of tributary load area. This permanent 3D record provides a basis for future support analysis should stability problems arise.
3.5.2 Potential leakage mapping, post-construction

Data collected during the construction phase can be analyzed for potential prevention of leakage as well as for comparison against later data. Differentiation in intensity values between dry and wet materials is documented by Lichti and Harvey (2002). For concrete, in particular, Lichti and Harvey’s (2002) experimental results show that both at near and far ranges concrete intensity values decreased when the surface was moistened. The significant difference in intensity allows for mapping regions of potential leakage where shotcrete has begun to absorb moisture.
Work by Sturzenegger et al. (2007) on seepage in rock slopes confirms this differentiability. No other factors, like lithology or dust/dirt on the surface, showed a similar intensity contrast. The contrasting intensity of wet and dry patches of newly applied shotcrete is seen in Figure 3-8. As anticipated, regions adjacent to bolts remain moist, highlighting leakage initiated by drilling. This ability to differentiate dry from moist may be equally useful in identifying key (open and water bearing) structural discontinuities now obscured by the liner. As seen in Figure 3-9 the differentibility of intensities is significant and does not require high point density. Train or truck mounted mobile scanning (Lato et al. 2009) for example, can be used to survey rapidly for leakage after construction is complete or in an older tunnel without interrupting traffic flow.

Figure 3-9: Raw point cloud from one scan illustrating 30 m section of tunnel showing contrasting intensities of exposed rock, dry shotcrete and wet shotcrete (in this case, wet due to seepage initiated by bolt drilling).
3.6 Geotechnical applications

The primary advantage for collection of LiDAR data during the excavation process, with respect to geotechnical applications, is that it allows for permanent documentation of ground conditions and detailed analysis after leaving the site as well as after the rock is obscured by support installment. Further, the scanning and alignment of subsequent rounds can be used to create more extensive rockmass models, enhancing the ability to identify key discontinuity features and key failure modes.

3.6.1 Analysis of structurally controlled overbreak

Structural discontinuity geometry information can also be used to evaluate the impact of structure on the ability to maintain the desired excavation geometry. Both zones where too much rock has been excavated (overbreak) and zones that have been insufficiently blasted to meet tunnel profile requirements (underbreak) can be identified in comparing the final rock model to the design model. Figure 3-10 shows a detailed analysis of a particular groundfall in one of the Akershus tunnels. The height above a semi-cylindrical tunnel is computed and displayed as coloured contours and the planes bounding the failure are imported to a mechanical model for back analysis. In addition, key joint sets can be identified and possible combinations of intersecting structure (wedges) can be analyzed with basic wedge failure modelling programs as shown in Figure 3-11 and discussed in the next section.
Figure 3-10: (A) detailed LiDAR model of a wedge shaped groundfall in the Akershus Tunnel (Oslo); (B) wedge contoured by overbreak height; (C) tunnel scale overbreak map; (D) mechanical model of unstable block.
Figure 3-11: (A) LiDAR scanning in the Akershus Tunnel; (B) two joint sets identified from LiDAR model (third set facing away from viewer); (C) Wedge geometry formed by 3 identified planes; (D) stereonet and wedge models from all unstable combinations of 5 joint sets.
3.6.2 Structural discontinuity evaluation

In order to optimize the time a geologist or geotechnical engineer spends at the face in a drill and blast tunnel operation, the authors propose the use of LiDAR scan data for rockmass characterization, in particular for mapping structural discontinuities. Traditional hand mapping at the face can be time consuming and is limited by safe access to the newly excavated tunnel section. The use of LiDAR data allows for detailed mapping of structural features at the office and allows the specialist on-site to spend more time on other characterization attributes, like alteration, water inflow and discontinuity filling. As discussed by Decker (2008), discontinuity analysis using LiDAR data has many advantages over traditional mapping, i.e. by hand with compass, including: digital rockmass documentation that can be reinterpreted by other specialists as well as increased quantity and accuracy of measurements with less time spent at the face/in hazardous zones. The extraction of discontinuity surfaces from point cloud data can be done either interactively and automatically. Figure 3-12 shows a 15 m length of exposed rock, three rounds of excavation, with 158 joint measurements identified manually. The results of traditional mapping (compass or clinorule) and interactive mapping of the LiDAR data, are found to be very comparable. The two main joints sets obtained had dip and dip direction: 60/078, 90/180 (traditional mapping) and 62/072, 88/177 (LiDAR data). It is important to note that a greater quantity of measurements is obtained by ‘virtual mapping’ than hand mapping and more significantly, the variation of discontinuity orientations is better represented. The reliability of the LiDAR measurements is greater since it is not affected by magnetic deviations, by the generalization of a large potentially variable joint plane to the results of a small sampling surface or by approximations made for hard-to-reach structures. The variation within a joint set as well as
random fractures are therefore far better represented by ‘virtual’ mapping conducted in the office with the evaluation of tunnel face LiDAR data.

Figure 3-12: (A) Bare rock model, meshed, aligned LiDAR data and (B) 158 identified joint surfaces from three 5m rounds, Sandvika site; (C) Stereonets of traditionally hand-mapped structural data and (D) manually extracted planes from point cloud, ‘virtual mapping’, where tunnel trend is N-S.

The authors have opted for manual feature extraction, which is conducted by selecting the data points falling on a surface that the interpreter deems to be a joint. While this method places more onus on the interpreter, the authors feel this is preferred over automated discontinuity
extraction which automatically identifies ‘patches’ in the data, i.e. groups of mesh triangles with similar normal vectors. Automated discontinuity feature extraction is attractive in its ability to 'objectively' detect discontinuities. However, the authors find that for underground applications where the rock face has been damaged during blasting, scaling etc., current algorithms are unable to provide acceptable structural information. Results from automated joint detection algorithms are often noisy (due to rock damage) which may cause any significant structural information to be masked while excessive automated filtering may remove key features. Mesh type is also critical for structural characterization (Lato et al. 2009). Simple draping mesh algorithms, incorporated in some software, limit the user to either interpreting the face or the crown, but not both simultaneously. This leads to severe bias challenges while more advanced and truly 3D tessellation algorithms provide a better solution (used in the examples presented).

### 3.6.3 Discontinuity spacing and 3-dimensional models

The advantage of 'virtual' structural mapping extends beyond statistical structural characterization but positions each discontinuity feature in 3D space, thus creating a rockmass model. This model can serve to evaluate discontinuity interaction and joint spacing. Extrapolations of joint features identified in Figure 3-12 are shown in Figure 3-13. The features are colored by common orientation, where seemingly random orientations remain in grey. This sort of analysis can be useful in efficiently evaluating joint spacing, potential locations of wedge failure as well as the prevalence of random joint orientations. Furthermore, this analysis can become part of the permanent digital rockmass documentation. The ability to extract the exact location and orientation of discontinuities in 3-dimensional space can also be advantageous for the creation of a very complete database for block modelling such as that shown in Figure 3-14. It is very important to note that for joints within a particular set, a bias against detection will exist in
certain portions of the scanner’s field of view. This is not a problem for statistical collection since different joint orientations will dominate different portions of the view. For discrete models (placing joints in their actual location) this is a critical issue. Figure 3-14 illustrates this point. The steeply dipping joint set in the image was observed to have similar frequency and spacing across the tunnel profile. In the LiDAR model, however, the detection of this joint set is hindered across the upper left part of the profile. Work is ongoing to understand and compensate for this bias.

Setting aside concerns about this bias for the moment, a joint spacing analysis is shown for the same bedding-defined set found in the shale-limestone unit at the Sandvika site. Figure 3-15A shows the planes identified along bedding and their extrapolation through the right side of the tunnel. A histogram is shown in Figure 3-15B, created from the measured joint spacings in this model. In this plot, the larger spacing records may be the result of the bias mentioned previously and would require correction.
Figure 3-13: Extrapolation of major joint surfaces and colored according to orientation, in order to identify key structural concerns (where grey are random orientation), three 5 m rounds in 10 m diameter tunnel, Sandvika site.

Figure 3-14: (A) 3-Dimensional block model constructed actual joints identified from LiDAR data. (B) Exaggerated block movement in mechanical model, highlighting potential instability modes. See text for note about bias. (Note: lines radiating from left springline are model construction lines - not joints).
Figure 3-15: (A) Identified and extrapolated joint planes. (B) Joint spacing distribution of joint planes identified.
3.6.4 Surface characterization

The high density of LiDAR data also allows for detailed analysis of joint surfaces themselves. Research in past years has attempted to use 3-dimensional LiDAR models to extract 2-dimensional joint surface profiles to be used in surface characterization schemes, e.g. JRC (Barton and Choubey 1977). Researchers have also proposed 3-dimensional fracture characterization methods in response to the increasing ability to collect and manipulate high density point cloud data sets (Haneberg 2007, Rahman et al. 2006, Fardin et al. 2001). Large scale roughness is distinctly identifiable but the ability to differentiate small-scale roughness from noise has yet to be demonstrated. Figure 3-16 shows a 10 cm vertical roughness profile along a joint surface at the Bånkall tunnel in northern Oslo obtained for comparison to the standard roughness profiles for JRC (Barton and Choubey 1977). This is equivalent to performing a manual measurement with a profile gauge.

Joint surface models from LiDAR data can also be analyzed by comparison against geometrical best-fit planes through the local point cloud. This method allows for an estimation of roughness amplitude to be made, i.e. the deviation from the average plane. This planar analysis allows for a more 3-dimensional characterization where anisotropy in the surface variation may be noted. If anisotropy on the fracture surface is present, particular attention should be paid to the selection of roughness profiles if they are to be used as a classification tool. Rock surface model of a large fracture plane is compared to best fit (average) plane and the deviation is contoured in Figures 3-17A. The approach is sensitive to the sizing of the measurement window (directly related to the scale of roughness) and the data density. The comparisons (deviation) between a larger and a smaller best fit plane of a different joint are shown in Figures 3-17B and C.
3.6.5 Identification of discrete and textural geological features

LiDAR data sets are highly advantageous in their ability to document discrete features in the rockmass, their orientation and position. This information is valuable for focusing monitoring efforts in these zones post-construction, as well as, for predicting conditions in adjacent excavations (i.e. twin tunnels or benched excavation). As seen in Figure 3-18 which is a raw point cloud with intensity (laser reflectivity) displayed, large scale discrete features maybe be easily identified and documented without any processing.

However, not all discrete features may be as obvious as this. A key advantage of collecting LiDAR data during the excavation cycle is the ability to simultaneously analyze rock that is now exposed and rock that has since been obscured by support installation. The alignment of scans from successive blast rounds is advantageous for identifying features which may only be

Figure 3-16: Large joint surface and 10 cm surface profile, Bånkall tunnel, compared to JRC roughness profiles (from Barton and Choubey 1977).
visible as lineations in the face. Features that may have been overlooked or dismissed after one or two excavation rounds may reveal themselves as significant over multiple rounds. A calcified shear zone is defined geometrically as a planar feature through three face scans and indicated in a photograph of the third round in Figure 3-19.

In addition to the ability of LiDAR interpretation to identify features of differing relief and geometry, the intensity values of the point cloud may also offer textural information of the scanned surfaces. Such textural information, similar to an oriented photograph, may offer additional geological characterization potential. Figure 3-20 below shows the raw LiDAR point cloud of the face at the Sandvika site. A large smooth failure surface reveals the ability to differentiate between interbedded shale and limestone layers/lenses based on differing intensities.
Figure 3-17: (A) Deviation of rock surface models from a fitted geometrical plane (field of view is 2 m). Note half barrels rendered in the data; (B) Contouring of joint surface with a best fit plane through a large data window and (C) a more local fit (higher data density as well). Field of view is 2 m.
Figure 3-18: A large scale discrete discontinuity crossing the face and right wall seen in raw point cloud with intensity displayed, Sandvika site.

Figure 3-19: (A) photograph of calcified shear zone in round 0+10 m. (B) Aligned face scans with intersecting planar shear zone, Sandvika site.
Figure 3-20: (A) Raw LiDAR point cloud of tunnel face with large planar surface on right. (B) Zoom-in of smooth planar surface where geological texture is visible due to alternating intensities of units, Sandvika site.

3.7 Conclusions

The application of LiDAR technology has been expanding and is rapidly becoming applied to new industries and projects. However, it is only starting to realize its potential in the underground environment, especially in the tunnelling industry. Numerous applications exist for the high density, high accuracy 3-dimensional point cloud models created. Data obtained during the active construction phase can be useful for both construction contractors and geotechnical personnel. In particular, the alignment of successive scans provides valuable information on both the rockmass and the supported excavation. The authors have been successful in the implementation of static LiDAR scanning at four sites near Oslo, Norway, including two active tunnelling operations.
LiDAR scanning at these tunnel sites and later in-lab analysis of the LiDAR data demonstrate:

- the ability to collect good quality data with a tripod setup in an active tunnel environment without disruption of construction workflow,
- the ability to obtain detailed quality control information on the precision of excavation and installed support, for use during construction as well as for permanent documentation, and
- the ability to retrieve representative rockmass information remotely and perform geotechnical analysis, both at the meso- and macro-scale.

Research is ongoing in this field including: the semi-automation of some of the processes discussed, the evolving methods of 3D roughness classification with point cloud data, the evaluation of additional rockmass classification parameters such as surface alteration or filling, and improving the ability to complete volume calculations.

3.8 Acknowledgments

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Chapter 4

Integration of 3-dimensional laser scanning with discontinuum modelling for stability analysis of tunnels in blocky rockmasses

4.1 Abstract

This paper proposes 3-dimensional laser scanning (LiDAR) as a new tool for underground rockmass characterization and stability analysis. As a drill-and-blast tunnel advances, LiDAR scanning allows for the documentation of the rockmass by collecting millions of rock surface point locations, in space, to create geometric scenes. Databases of geo-structural data (joints) can be produced by interpreting the “virtual” rockmass. These databases, which include the location of each measurement, can be much more extensive than what is obtained by hand-mapping in traditional geotechnical data collection. The advantages and challenges of LiDAR data for underground rockmass evaluation are discussed. The joint database can be used in discontinuum modelling in order to evaluate structurally-controlled failure in blocky rockmasses. These joint system models, either statistically generated or discretely represented, can be far more representative block models than was previously possible, due to the wealth of joint measurements and joint position information. However, a number of pitfalls can occur.

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authors present a workflow, from data collection and analysis to design outputs, for integrating LiDAR-derived data into rockmass stability modelling.

4.2 LiDAR for geotechnical assessment

Tunnelling projects are consistently under the pressures of contract timelines, budgets and safety requirements. In order to provide the best engineering recommendations possible, tunnelling engineers must collect accurate, representative geotechnical information to select an appropriate excavation method, primary and secondary ground support and perhaps long-term monitoring. By trying to apply developing technologies to underground mapping pursuits, the tunnelling industry has the potential to take advantage of efficient, accurate techniques for geotechnical data collection. One technology showing great potential is 3-dimensional laser scanning, also known as LiDAR (Light Detection And Ranging). LiDAR uses transmitted laser signals to record millions of highly accurate points in space to create a 3D, geometrically-correct "image" of the scanner's surroundings. Points are defined in an (x,y,z) coordinate system relative to the scanner, as well as being assigned an "intensity" value (i) which is a function of the surface reflectivity. The millions of points in space are referred to as the “point cloud”.

4.2.1 LiDAR for underground rockmass characterization

The original geotechnical application of LiDAR was slope surveying and hazard assessment (Bitelli et al. 2004) and over the years has progressed to assessing geologic structure at the rock outcrop scale (Mah et al. 2008, Kemeny et al. 2006, Lato et al. 2008, Slob et al. 2005). Some have endeavored to recreate 3D block models based on rock structure detected in LiDAR data (Ferrero et al. 2009, Voyat et al 2006). However, only a limited amount of development of LiDAR techniques for underground applications has taken place. To date, the primary underground application has been contract specification verification, for example final tunnel
geometry (Decker 2008, Seo et al. 2008). It has been demonstrated that there are several operational applications of LiDAR data collected during tunnel excavation (Fekete et al. 2010). Other attempts have used LiDAR for tunnel deformation monitoring (Van Gosliga et al. 2006, Lemy et al. 2006). Some underground photogrammetry work, which creates a similar point cloud data set, has successfully mapped geological structure (Gaich & Potsch 2008). Many of the data extraction techniques that have been used for rock outcrop mapping at surface can be applied, with adjustments, to the underground environment. Point cloud data from triangulation-based laser imaging implemented in an underground mining environment has been shown to effectively map rock structure when compared to hand mapping results (Mah et al. 2008).

If LiDAR scans are conducted at a non-obscured drill and blast tunnel face, the project can greatly benefit from the ability to perform detailed rockmass characterization with the scan data. Primary advantages of LiDAR scanning as the tunnel advances include permanent 3D documentation of the rockmass conditions before the liner obscures geological structure and the ability to document discontinuity features that would be inaccessible to mapping personnel either due to location or safety concerns. Large geo-structural databases are possible with LiDAR data interpretation, though research efforts have yet to identify the most effective way to implement the wealth of data. This paper proposes a workflow, from data collection to design outputs, for the integration of LiDAR technology into the creation of complex, representative 3-dimensional discontinuum models.

4.3 Data collection

The practical deployment of LiDAR scanning in the active tunneling environment has been demonstrated by the authors in a collaborative effort between Queen's University (Kingston, Ontario) and the Norwegian Geotechnical Institute (NGI) in Oslo, Norway. LiDAR scanning was
conducted by the authors at five active headings (10-15 m diameter) at two drill and blast project sites over multiple rounds, and at three completed unlined rock tunnels (4-8 m diameter). The active tunnels were part of a railway expansion project near Oslo, Norway. For this paper, the “case-study rockmass” to be used as the example for LiDAR integration into geotechnical stability analysis is from a 10 m diameter tunnel at the Sandvika site that is part of the railway project. For scanning in an operational environment, a stationary tripod setup was used and scanning was done after blasting, mechanical scaling and manual scaling. The tripod was set up at the limit of supported rock, approximately 7 m from the face. A distance of 0.5 to 1 tunnel 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 with range noise calibrated to be 0.6 mm rms for a low reflectivity (20%) target at a distance of 10 m. The high speed data collection (up to 500,000 points per second) makes this an ideal system for quick deployment in an operational tunnel environment. Fig. 4-1 shows 3D laser scanning sessions at the Sandvika and Skallum project sites near Oslo, Norway.

Figure 4-1: LiDAR scanning at a 10 m diameter tunnel face (A) and in an enlarged intersection (B) Oslo, Norway.
4.4 Overview of data processing

Raw LiDAR point clouds can be used for visualization, but in order to perform any analysis or measurement, data management is required. File sizes can be up to many GBs in size and so reduction of the data to manageable size/format is required for quick visualization and feature extraction. Processing techniques are not the focus of this paper but have been discussed by various researchers (Fekete et al. 2010, Lato et al. 2008, Kemeny et al. 2006, Seo et al. 2008, Sturzenegger et al. 2007). An example of the construction of an aligned tunnel surface model from the point data of three 5 m blast rounds is shown below (Fig. 4-2). A basic processing workflow is summarized below:

A. Reduce data set to zone of interest (and decimate data overall)

B. Create surface model (meshed data, where points are grouped into triangles)

C. Align with scans of previous face position or translate to absolute coordinate system (geo-referencing)

D. Measure/interpret and extract data (see discussion in Section 4.5)

Figure 4-2: Process of taking raw points (A), creating meshed surface models (B) and aligning three surface models to create a tunnel model (C). Three LiDAR scans at the face of 10 m diameter tunnel are combined. Each scan at the face follows a 5 m advance (towards the left) and is displayed in a different color. Only the rock surface is visible in this view.
4.5 Extractable information for rockmass characterization

Significant research effort has sought to improve our ability to perform geotechnical evaluation of rock outcrops using LiDAR data (Slob et al. 2005, Kemeny et al. 2006). Many of the lessons-learned can equally be translated to the application of LiDAR underground. The key geotechnical information that can be extracted includes joint location and orientation, joint set spacing, structural overbreak and estimation of joint roughness (Kemeny et al. 2006, Fekete & Diederichs 2010). A discontinuity surface (joint) is extracted from the data by fitting a best-fit plane to a selected region of points (Fig. 4-3A). The plane is defined by a normal vector \((X,Y,Z)\) and an origin \((x_p,y_p,z_p)\). With a geo-referenced tunnel model or a known tunnel alignment, true dip and dip-direction can be calculated. Otherwise, orientation relative to the tunnel centre-line can be used. While automated joint identification has been implemented in some software, it has only been successfully used for rockmass characterization in high-relief rock slopes with obvious structure. Based on the experience of the authors, current automated joint selection algorithms are not sophisticated enough to distinguish between blast damage, scaling etc. and therefore should not be employed for underground mapping. For the research presented, ensuring that the joint database was reliable was more important than the additional time spent for interactive joint selection. Fig. 4-3B illustrates several joints identified in the same tunnel advance. Each joint is extrapolated into a circular joint plane that intersects the surface model. Joint spacing analysis can be conducted in several ways: either within the point cloud processing software, by geometric calculation in spreadsheets or after planes have been modelled in a discrete element program. Based on the streamlined wizards, for calculations like joint spacing that are available in photogrammetry software like JointMetriXAnalyst (3G Software and Measurement), the future will hopefully bring straightforward, efficient software designed specifically for assessing
geotechnical parameters in LiDAR data. Fig. 4-3C shows the extrapolated joint planes of a pervasive set along tilted bedding, intersecting the LiDAR surface model. It is recommended that joint selection is conducted by personnel who have been to the tunnel face. A LiDAR data interpreter with experience of the rockmass in question can conduct a more discriminating selection of joint planes and thus reduce the inclusion of fractures due to blast damage or scaling.

Figure 4-3: (A) 'Virtual' joint mapping is conducted in the tunnel crown of meshed LiDAR data by selecting a region of points and fitting a best-fit plane. (B) Joint planes are extrapolated to circular planes that intersect one round of LiDAR data collected at the tunnel face. (C) Joints along tilted bedding in the crown and right sidewall are extrapolated to intersect the tunnel along three 5 m advances.
4.6 LiDAR as a tool for rockmass modelling: discrete element model construction methods

As stated by Barla and Barla (2000), “the key to the success” of assessing tunnel stability “is the level of understanding achieved in describing the rock mass conditions”. If a large, representative structural database can be extracted from LiDAR data, the level of detail allows for a better understanding of the rockmass and thus a more successful assessment of stability conditions. When stability of the rockmass is dominated by movement along discontinuities, typically blocky ground with low to moderate field stresses, a discontinuum model is most appropriate. By including the many planes identified in the 3D laser scan, a representative 3-dimensional discrete element model (DEM) has the potential to recreate observed rockmass behaviour and predict future ground conditions. As described by Ferrero et al. (2009) who used similar procedures to recreate rock slope geometry, there are two primary methods of translating structural survey data into DEMs. For the present paper, the authors offer the following definitions:

**Deterministic reconstruction:**

a jointed rockmass model constructed from discretely measured discontinuities in LiDAR data, each unique plane defined by a specified orientation and position;

**Statistical reconstruction:**

a jointed rockmass model based on the interpretation of discontinuities into joint sets with statistically variable orientation and spacing.

The numerical models presented are distinct element models constructed in ITASCA's 3DEC (v. 3.00, 2004). The use of rigid blocks in these models is justified by shallow tunnel depth and a blocky rockmass where failure manifests itself as displacement along joint planes. The use of rigid blocks was also required to stay within the limitations of computer hardware and for practical computation times. The presented tunnel models simplify insitu conditions to $K_o=1$, with vertical stress equivalent to 25 m of rock overburden. For numerical stability, a minimum
cut length tolerance must be specified. When the cut tolerance is larger than the edge length of blocks at the boundary of the tunnel, these blocks remain “un-cut” and protrude into the tunnel. Thus, in order to fully excavate the tunnel, a small cut length tolerance must be used.

Both methods require the extraction of discontinuities from LiDAR data as discussed in Section 4.5. The greater the quantity of unique 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 in more than one position (i.e. crown and sidewall). In order to demonstrate the impact of indiscriminate joint selection, two joint spacing calculations were conducted for the same joint set and plotted in histogram form (Fig. 4-4A). One calculation used indiscriminate picking, while the second calculation was done after a more careful re-screening of the data. The indiscriminate picking could be equivalent to a novice geo-structural interpreter, selecting all small near-planar surfaces as joint planes. The re-screening was conducted manually by extrapolating joint plane to ensure that the same joint plane was not selected more than once along the tunnel span/length. As well, the re-screening aimed to reduce the number of blast-fractures included in the data by on visually inspection of each plane. The average joint spacing without filtering is on average 0.1—0.25 m. In comparison, the average joint spacing following this redundancy filtering is in the 0.25-0.5 m range. This issue of double-counting planes can be particularly challenging in larger tunnel spans. The interpreter may classify two outcroppings of the same joint as two unique planes if small deviations in plane orientation cause the extrapolation of one outcropping to not match up with the other (see schematic in Fig. 4-4B). The deviation may be due to variation in the joint plane itself or due to the interpreter selecting a small portion of the exposed joint surface that does not represent the broad attitude of the plane.

Double-counting the same discontinuity can hinder the ability to make the most representative rockmass model in both deterministic and statistical reconstructions. In a deterministic model, duplicated joints can create computationally challenging, non-real narrow
wedges and over-concentrate fractures at the tunnel boundary. In statistical reconstructions, double-counting of joint planes causes over-weighting in statistical analysis and may cause a set to appear more prominent than in actuality. As illustrated in Fig. 4-4A, double-counting can also result in a much tighter spacing than is accurate. Flawed spacing evaluation creates unrepresentative block sizes in numerical modelling which could be pivotal in support decisions. Thus, careful data filtering to reduce redundancy is strongly recommended. The authors found that extrapolating joint planes across the entire tunnel model helps with the filtering process. These results of Figure 4-4 also highlight the significance of the interpreter’s skill at point cloud interpretation and experience in geo-structural mapping. If joint planes are found in general to be planar for a given rockmass, an automated filtering program could be written by prescribing a particular angular tolerance between planes that intersect. If joint surfaces are undulating, an automated filter would be more difficult to implement.
Figure 4-4: (A) histogram showing joint spacing values for all selected joints and for joints after redundancy filtering. (B) A schematic illustrating how slight deviation in measured orientation may cause a single joint plane to appear to be two distinct planes, causing double-counting.

4.6.1 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. Thus, discontinuities are focused around the excavation and fewer
blocks are created in the more distant rockmass. Joint strength parameters are applied to the joints. These may be approximated by roughness evaluation on site or in LiDAR data, based on past experience or as determined in lab testing. Interpretation is required for determining an appropriate joint persistence. 3DEC code represents persistence as a percentage of successful cuts. For example, a joint with a persistence of 0.8 will successfully cut 8/10 blocks that it traverses. This definition of persistence is a simplification of the paths of real joints and is a limitation of the software. This method of incorporating persistence into the models may restrict the ability of the rockmass model to be fully representative of the actual rockmass.

Joint persistence remains challenging to evaluate for all modelling exercises as one can never “see” the full extent of a joint surface in a tunnel excavation. Given that each discontinuity input into the deterministic model is 'real', one might be tempted to not limit joint persistence. However as noted by many rock mechanics experts, joints begin and terminate and rock bridges remain. If DEM joints are assigned full persistence, this will underestimate rockmass stability. Challenges with assigning persistence values and their influence on the model will be further discussed in Section 4.8.3. Fig. 4-5 illustrates the construction of a deterministic model with 90 joints over a 15 m length. As can be seen in the illustrated progressive construction of the model, the quantity of joints input into the model has a dramatic impact on final rockmass. It is thus important for the interpreter extracting joints from the LiDAR data to be wholehearted in his or her efforts.
Figure 4-5: Construction of a deterministic model of 90 joints with 100% persistence. Model showing increasing number of joints (A to C); Final jointed model (C) with tunnel excavation (D).
4.6.2 Statistical Reconstruction

Relative to the deterministic method, statistical reconstruction requires additional steps with increased user interaction. In addition to data management, discontinuity orientation data must be interpreted via stereonet into joint sets with statistically variable orientation. In a rockmass with definite joint sets, this may be an easy task. Some rockmasses may have more variation in joint orientation and one or two “sets” with highly variable orientation may be required to capture random fracturing in the rockmass. To confirm the suitability of statistical characterization of joint orientation, the construction of a synthetic joint database with the interpreted statistics in a utility such as JDIST in DIPS (RocScience, 2008) may be helpful. The selection of sets from the LiDAR-extracted joint data and the confirmation of statistical parameters by comparison with a synthetic collection of joints are demonstrated in Fig. 4-6. In this particular example, two very prominent joint sets (J1, J2) and a third, moderately prominent set (J3) are identified. Two other joint sets (J4, J5), which are more variable, are also delineated. Due to the large variability in orientation, joints falling within these grouping (J4, J5) do not necessarily belong to a specific “set” but rather to a preferential orientation of fracturing. In other rockmasses, fractures may be fully random and could be simulated in the model by including a “set” covering the full stereonet. Mean spacing and spacing variability can be determined as discussed Section 4.5. The progressive construction of a statistical model is illustrated in Fig. 4-7. The statistical model was restricted to four joint sets in order to simplify the model to a practical size. Of the two highly variable joint sets (J4, J5), J5 was omitted because it was deemed less critical based on kinematic analysis of wedges created with this combination of joints.

The statistical rockmass models that are presented within this paper serve to illustrate the feasibility of constructing models from LiDAR-based characterization rather than ideal models.
This is due to the limitations of joint network representation already embedded in the selected software. The statistical parameters used were limited to those provided in basic ITASCA codes, i.e., standard deviation of orientation and random deviation of spacing about a mean. More appropriate distributions may be employed with additional coding effort and would likely augment the representativeness of the models. This would be especially true for joint distributions that are anisotropic or not normally distributed about the mean.

Another limitation is that the first joint set will always be fully persistent (as long as orientation variability is not so great as to cause joints within the set to intersect each other). This is a function of the 3DEC definition of persistence which requires the opportunity to intersect other joint planes. Thus in order to reduce the joint size of the first joint set, “dummy” joint sets were implemented in model construction. These “dummy” sets were entered prior to the creation of the first joint set at a perpendicular orientation. By assigning very high joint strength they did not lower rockmass strength, but allowed for the first joint set to be discontinuous. “Dummy” sets were only required for simulations of the low end of average rockmasses persistence (50%).
Figure 4-6: Joint orientation data extracted from 3 scans of successive tunnel faces, with sets defined and labeled (top) and synthetic joint orientation data constructed from set statistics to visually confirm representativeness of statistics (bottom).
Figure 4-7: Progressive construction of a statistical model by joint set sequence (A-C). The final rockmass model, 4 joint sets (C), and tunnel excavation are shown (D). (Note: faint lines radiating from tunnel profile are model construction lines, not joints, and do not allow movement across their boundaries).
4.7 Evaluation of DEM reconstruction methods

Due to their very different inputs, the deterministic and statistical reconstruction methods offer different advantages and limitations. The authors find that their respective strengths make them more or less suitable for certain applications of numerical modelling, such as back-analysis or forward modelling.

4.7.1 Deterministic method: benefits and criticisms

The deterministic method is advantageous in that it represents real, discrete structural features, which may not be captured in rockmass classification. This would be especially beneficial when a feature such as a weak fault zone is critical in tunnel stability. In other words, where stability is governed by non-repeatable structure, the deterministic method is far more appropriate. 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. This is of even greater concern if deformable blocks are to be used. For example, if we consider the number of blocks occurring within 2 m of the 10 m diameter tunnel profile (excluding excavated blocks), 63% of the total blocks in a deterministic model (3,400/5,400) occur in this region, in comparison to 32% of the statistical model, which also has a much higher number of total blocks (7,800/24,000). In other words, the statistical model has more than double the number of blocks in the region adjacent to the excavation, but the deterministic model offers an economy of joint density. Furthermore, the deterministic method is ideal for revisiting completed tunnel sections with overbreak to assess the contribution of structure. A better understanding of structural constraints (orientation and spacing) and resulting block sizes allows for a re-evaluation of tunnel support. As will be demonstrated in Section 4.9.1, the deterministic model can validate block behaviour in the DEM against actual tunnel performance. Successful back-analysis with a
deterministic model can be used to calibrate joint strength parameters and persistence for other numerical models.

However, disadvantages of this reconstruction method also exist. The deterministic method is less likely to characterize general rockmass character and thus is not an ideal predictive tool for design. Because this model only includes the planes that were actually detected in a particular section of tunnel, it may not be representative for other sections. The concentration of fractures at the tunnel walls is not adequate if block displacement occurs deeper into the rockmass, for example when very blocky ground causes tunnel convergence. Furthermore, if original joint selection in the LiDAR data is not done with scrutiny as discussed in Section 4.6, one or two falsely selected planes could greatly affect the modelled rockmass stability.

4.7.2 Statistical method: benefits and criticisms

Statistical rockmass reconstruction is advantageous in that it is more appropriate for general rockmass stability rather than the analysis of 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. While interactive picking of discontinuities in LiDAR data is currently user-dependent and therefore leaves some room for misinterpretation of blast-induced fractures etc., statistical use of the data helps to reduce the impact of any one stray measurement. Further, statistical models are useful in conducting sensitivity analyses. The modeller can assess the range of rockmass behaviour, for example, over a range of joint spacing values. When tunnel engineers have an understanding of possible rockmass behaviour for variations of the observed ground conditions, they can quickly adapt support in later tunnel sections.
Conversely, the disadvantage of a statistical reconstruction is that it does not make full use of the data collected: specifically, the actual location of discontinuity surfaces. Furthermore, it relies on mathematical assumptions of variability distributions of orientation and spacing, which may or may not be appropriate. 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.). There has long been debate over which statistical distribution is best.

The increased interpretation required to construct the statistical model can be seen as both an advantage and disadvantage. For an experienced modeller/tunnel engineer, the ability to better tune the model to the geological interpretation is valuable. However without this experience, deviating from a representative model could easily occur with a single misguided interpretation.

Thus the authors conclude that both methods have their limitations. Perhaps a hybrid method might optimize the combined use of discrete structural data near the tunnel with a statistical characterization of the broader rockmass. On the other hand, hybridization might simply use the locations of discrete planes from prominent joint sets as seeds for joint sets described statistically. The hybridization of construction method may require moderate to significant coding effort but would likely benefit from the advantages of both reconstruction methods.

4.8 Challenges of building rockmass models from LiDAR data

While LiDAR-derived databases can be impressive, unique features of LiDAR data and how it is to be implemented should receive special consideration. Personnel that use the data for modelling etc. must be aware of the implications of the challenges presented below in order to be able to interpret the data appropriately and to be able to create representative models.
4.8.1 Bias in LiDAR-extracted structural measurements

Because LiDAR is a line-of-sight technology, there are limitations on the completeness of the surface model that can be created including the sampling of certain joint surfaces. The scanner cannot “see” around corners or protrusions and so high relief tunnel walls will create what are known as “shadow zones” in the data (Sturzenegger et al. 2007). These are not usually very problematic, as long as the laser scanner operator makes an effort to position him or herself during scanning such that these shadow zones are minimized.

What is more problematic is inconsistent joint surface sampling due to orientation. Few points will be collected on surfaces that are near parallel the laser line-of-sight. Only surfaces that face the scanner obliquely will be well sampled by the scanner (Lato et al. 2010). As stated explicitly by Ferrero et al. (2009), “the accuracy in discontinuity plane interpolation depends on an appropriate sampling of the discontinuity itself”. When a surface is well sampled (many data points), dip and dip direction can be very accurately determined. However, Ferrero et al. (2009) find that planes are more difficult to sample if they are near parallel to the scanner line-of-sight and have unfavourable geometry (i.e. very small or elongated) or have large-scale roughness. Poor sampling can be the source of inaccuracy. Extensive testing of orientation inaccuracy related to joint shape sampled and the number of data points per joint has been published (Ferrero et al. 2009). Findings include the observation that dip direction is far more susceptible to inaccuracy (typically 5°-15° error versus up to 3° error for dip), but can be minimized by increasing the number of data points (Ferrero et al. 2009). These findings emphasize that careful joint plane selection is important and that the interpreter should aim to include the largest joint area possible for orientation calculation. The data interpreter cannot affect the joint angle relative to the scanner once the data has been collected, but must be aware of possible inaccuracy. The schematic in Fig.
4-8 illustrates the two ways in which bias can affect the sampling of joints. Fig. 4-8A illustrates that, in the three generalized locations (crown, face, sidewall), different joint orientations will be sampled more or less adequately, where a darker line represents a plane that is better sampled. The implication of Fig. 4-8A is that certain joint orientations may be visible in one wall/surface and undetectable in another, despite their actual presence. Fig. 4-8B illustrates that for the same joint orientation, the scanner’s ability to characterize the plane is a function of its orientation relative to the scanner, and thus its position in the tunnel profile. The implication of Fig. 4-8B is that if we attempt to characterize the spacing of a particular set, only certain areas of the tunnel can provide adequate exposure of the set for assessment. An actual example of the type of bias in Fig. 4-8B is highlighted in Fig. 4-9, where the joint set parallel to tilted bedding is exposed frequently in the right haunch, but rarely in the left sidewall. If bedding thicknesses are consistent in this unit, the LiDAR-extracted structural data can only adequately describe set spacing in one zone of the tunnel profile. The graph in Fig. 4-9 shows the calculated spacing of this joint set laterally relative to the tunnel centre-line and emphasizes that spacing is greatly underestimated in the left sidewall and haunch.

The established method of reducing bias is to collect data from more than one scanning position (Lato et al. 2010). By adding the data together, shadow zones and overlooked joints are reduced. This is highly recommended for slopes where the scan operator likely has the ability to move parallel to the slope. However, due to the limited extent of mobility underground (staying in supported ground etc), this may not be possible or very helpful. A significant change in perspective is required to fill in shadow zones.
Bias correction for traditional joint hand-mapping has long been developed. As noted by Lato et al. (2010), new correction factors had to be developed for the bias of LiDAR-extracted planes due to the dissimilarity with the bias of scanline/borehole data. However, the correction developed by Lato et al. (2010) assumes that data lies in approximately one plane (the slope face). Correction for a tunnel would require a division of the data based on the plane it lies in. This would require additional data management, including tagging extracted joint features with the plane in which they were identified. Each collection surface (right sidewall, left sidewall, back, and face) would have to be corrected separately. This correction would be particularly challenging in excavations that are circular or arched where data is not simply collected from 3 orthogonal orientations. However even when one chooses to use such correction factors, the
correction only improves the relative presence of different joint orientations and does not ameliorate the issue illustrated in Fig. 4-8B. The ability to assess joint spacing for a statistical model still cannot be conducted over the entirety of the tunnel.

Figure 4-9: Bias due to joint plane position relative to the scanner is exposed by tilted bedding planes which are poorly sampled in the left sidewall relative to right haunch. Only the discrete planes identified in the LiDAR data and interpreted to belong to J1(along bedding) are shown. The bedding planes input into the DEM illustrate discrepant sampling (top). Graphical representation of calculated joint spacing relative to tunnel centre line (bottom).
When using the scanline technique in joint hand-mapping, Priest (1993) suggests that three orthogonal scanlines greatly reduce sampling bias though do not eliminate it completely. This may suggest that the ability to collect joint measurements along the entire tunnel profile would sufficiently reduce the influence of bias from any one plane of collection. This data self-correction would only be present in statistically reconstructed models.

LiDAR has complex bias issues because the scanner can only sample a plane that is exposed on the tunnel surface (i.e. intersects it at some angle), but simultaneously has difficulty sampling joints which intersect perpendicular to the surface, due to line-of-sight issues. This complexity and the influence it has on collecting structural measurements from LiDAR data is best demonstrated with an example. Fig. 4-10 documents a special case where a joint set parallel to face becomes very difficult to characterize. The set is well documented only when it is exposed in the tunnel face, where it is perpendicular to the laser’s line of sight. Within a single face, it appears several times indicating very tight spacing. So, in a deterministic model, this joint set would be appropriately included when it occurred in the face but would be far underrepresented otherwise. Even if statistical reconstruction is pursued, the spacing is a challenge to interpret because the joint set only appears every 5 m with a new advance and new face. A joint of this orientation was encountered by the authors at the Sandvika tunnel site, see schematic in Fig. 4-10.

A graphical representation of calculated spacing is also found in Fig. 4-10. Very tight spacings are identified at the face positions (9, 14, and 19 m) where the joint plane has excellent exposure, but spacing is apparently large in-between advances. The plane parallel to the face becomes invisible to the LiDAR scanner in the tunnel walls and crown because it only appears as a trace, even though for traditional hand-mapping this would be the best orientation to sample the spacing on. Based on the observations of this particularly challenging joint set, the least preferred joint
orientation for sampling with LiDAR scanning would be those parallel to the face, sidewalls, or back (for a non-arched profile).

Figure 4-10: Schematic of longitudinal cross-section of advancing tunnel heading demonstrating the limited ability to capture a joint set parallel to the tunnel face with LiDAR scanning, where dark lines represent planes that are well sampled and pale grey lines are poorly sampled (top). Graph shows the calculated joint spacing relative to the tunnel advance, where dashed lines are tunnel face positions (bottom).
4.8.2 Implications of bias in LiDAR data for joint network reconstruction

It has been demonstrated that bias in LiDAR data can be significant and that, without mindful data collection and interpretation, meaningful rockmass modelling is not possible. The authors offer the following recommendations for optimizing data collection at the face:

- If occlusion is of great concern and it is practical, two scanning locations, with as significant a distance between them as possible (relative to the tunnel diameter), should be used to reduce the extent of shadowing. While an additional scan will nearly always improve coverage at least to some degree, it would only be necessary (and worth the additional data processing/management) when significant relief in the excavation walls would lead to large gaps in the point cloud.

- Scan operator should be strategic in scanner positioning, when possible in larger spans, and aim to minimize the number of the prominent discontinuity planes that become invisible to the scanner, especially if deterministic reconstruction is to be pursued.

- Personnel at the face during collection should note prominent joint sets, approximate spacing and its variability, in order to more wisely approach data interpretation later. This will enable the modeller to support interpretations for the statistical model as well as more confidently proceed with a deterministic model.

No matter the precautions in data collection, some bias will remain. Personnel that interpret the data and apply the results to design must be aware, not only that the bias exists, but specifically how bias will affect the model and the corresponding strategies to reduce the propagated error. The consequences of bias vary between the two reconstruction methods.
The consequences of bias in statistical reconstruction include:

- Clusters of joint orientations may not be representatively weighted, but the ability to extract data from orthogonal planes helps to reduce bias. If very accurate weighting is required, correction factors, based on the plane of data collection, may be applied with additional effort. These correction factors remain to be developed for underground data sets.

- Spacing should be cautiously evaluated. If on-site experience suggests that spacing is constant across the tunnel span, the zone where that particular orientation is best exposed should be used in preference to the average value calculated from the full span.

The consequences of bias in deterministic reconstruction include:

- Some planes that are exposed in the tunnel but have an unfavourable location/orientation for scanning will be left out of the model.

- Sampling of a particular joint set will not be consistent from one zone of the tunnel profile to another and therefore model block sizes will vary inappropriately.

### 4.8.3 Challenges of joint persistence evaluation

Discontinuity size remains “one of the most difficult discontinuity properties to measure accurately” (Priest 1993). While the exposed joint surface area in the tunnel may give an indication of persistence, the full joint extent will never be consistently exposed, termed “censoring bias” (Sturzenegger et al. 2007). Thus methods of estimating persistence must be pursued. Traditional methods typically use trace length from scanline surveying as an indicator of persistence (Priest 1993). Sturzenegger and Stead (2009) remain loyal to trace length for persistence measurements in LiDAR data from a rock slope and calculate trace length from exposed joints in a sample window. They find that laser scanning actually does a better job than
traditional methods of evaluating medium to high persistence joints (>3 m). However, Sturzenegger and Stead (2009) do not address the challenge of following traces in LiDAR data. In contrast to photo documentation, LiDAR scans accurately sample joint surfaces but more poorly define joint traces because the scan relies on data points rather than continuous data. Because of the low relief of the tunnel face/walls (in comparison to a rock slope), the authors do not feel that the exposed joint surfaces adequately represent joint persistence. The ability to use joint traces would help to reduce this underestimation of persistence, but again, these remain difficult to visualize with a point cloud. Alternative techniques or appropriate corrections to trace length estimates must be developed. Strouth and Eberhardt (2006) prefer to evaluate “exposed persistence” from the longest dimension of a selected joint surface on a rock slope and accept that this will provide minimum persistence or a lower bound of average persistence. Ferrero et al. (2009) suggest a combined approach by extrapolating the 2D trace length concept to 3D and using point cloud data, associated images and specialized software to evaluate persistence. From there, “a hierarchy of probabilistic distributions of fracturing” is used to implement the estimated persistence into rockmass modelling (Ferrero et al. 2009). Further research in persistence evaluation in point cloud data is needed in order to fully make use of the rockmass documentation.

The challenge of characterizing persistence of sets or individual joints adds an additional step of interpretation for all rockmass block model reconstruction. This is significant because a misunderstanding of persistence can lead to a faulty evaluation of removable blocks and false block size being used in design.

While LiDAR data does not yet provide the ability to evaluate persistence directly, deterministic models can used in back-analysis to estimate persistence. By calibrating against the
actual removable blocks in the tunnel observed after scaling has been completed, the interpreter
can assign a persistence value to joints in the rockmass. In order to calibrate, the modeller must
have a good idea of joint strength. In the context of the Mohr-Coulomb criterion, analysis of
surface roughness in dense LiDAR data can provide a good estimate of frictional strength (Fekete
et al. 2010). Thus, only cohesion due to the contribution of rock bridges remains to be evaluated.

Furthermore, LiDAR-based rockmass models can be used to assess the impact of
determination on a representative rockmass block model. By varying the joint persistence, the
modeller can learn the sensitivity of rockmass stability to persistence. Given that “the impact of
persistence is underrepresented in current rockmass classification schemes” (Kim et al. 2007), it
would be a great contribution if discontinuum models could evaluate this impact. An extensive
sensitivity analysis for several rockmasses may be what is required to develop a better way of
accounting for the impact of persistence in classification schemes. Below the authors present the
results of a persistence sensitivity study for a single tunnel, in the case-study rockmass, applying
both deterministic and statistical reconstruction methods. The work presented represents an
introduction to the more extensive research that should be pursued.

4.8.3.1 Influence of persistence on deterministic model

For the construction of the deterministic model, joints were sorted into two primary joint
sets (J1, J2 in Figure 4-6) and more “random” jointing in order to better represent the geological
setting. This sorting was used for the order of joint input as well as for a graded application of
persistence values. The two prominent sets always had greater persistence than the lesser
sets/random fractures (e.g. J1: P= 100%, J2: P= 80% and Jother: P= 50%). For the presented results,
a block that has been “released” is defined as having a displacement greater than 0.05 m. In order
to better capture the influence of persistence and more fully explore the kinematics of a particular
rockmass geometry, arbitrarily low joint strength was used (Friction: 25^0, Cohesion: 0.01 MPa, Tensile strength: 0 kN). Higher joint strength, which would be more appropriate for most joint surfaces, would likely make the trend more subtle and make it more difficult to characterize the influence of persistence, especially at the lower end of the persistence scale.

The results of the sensitivity study for the deterministic reconstruction are presented in Fig. 4-11, where the quantity of released blocks is analyzed for a range of average joint persistence (where “average” joint persistence is calculated from the ~90 discrete joints included). Model results show that the number of removable blocks increases dramatically with increased persistence. It is important to note that the trend in Fig. 4-11 is for one particular method of numerically describing persistence (successful percentage of cuts). While the general increasing trend should be valid for all mathematical representations of persistence, other models such as discs, polygons etc. would likely produce curves with varying tendencies. The results of Fig. 4-11 appear to be consistent with the findings of Song et al. (2001) who used a joint disc model in a program called BLOCSTAB. They found that the “volume of removable blocks increases exponentially as the mean diameter of the joint set linearly increases” (Song et al. 2001).

In the present study, when average persistence was greater than 65%, a greater increase in released blocks occurred (increased slope of the line in Fig. 4-11). The fact that actual block release in the tunnel from which these joints were collected was minimal, further confirms the fact that high joint persistence or continuity should not be assumed. Overestimating persistence in such a way during the design phase of a project would lead to recommending unnecessarily high support capacities. This should serve as further warning against relying only on the deterministic method for structural stability assessment, because without proper calibration, results will be
unrepresentative. Fig. 4-12 is a visual demonstration of two extremes in rockmass stability of deterministic models, which vary only in joint persistence. Fig. 4-12B shows a collapsing rockmass resulting from a joint network with 100% persistence, which though not a possibility, is helpful for illustrating the influence of persistence.

Figure 4-11: Total number of blocks that have exceeded displacement threshold (0.05 m) for a given average persistence.
1.8.3.2 Influence of persistence on statistical model

A comparable sensitivity study was conducted for a simplified statistical model of a tilted sedimentary unit. The simplified model uses constant joint spacing for all four joint sets and the same persistence for all joint sets. With a simplified model, clear trends of block release relative to persistence are documented (Fig. 4-13). For the 3 spacing values tested, consistently more blocks were released as persistence increased, where the rate of increase was greater when joints were more tightly spaced. If the persistence is related to total volume released, a slightly different trend emerges for widely spaced joints (Fig. 4-14). For the model with 1 m joint spacing, a greater block volume is released at persistence (P) of 50% than at P= 70% and 80%. This can be
attributed to the release of one or more large blocks that have been formed by the combination of wider spacing and lower persistence. Otherwise the trend remains the same: the higher the persistence, the greater the volume of overbreak. The rates of increasing block volume released relative to persistence are comparable between the three spacings tested.

Figure 4-13: The relationship between the quantity of displaced blocks in statistical block model and joint persistence for 3 joint spacings (where displacement threshold is 0.05 m).

Figure 4-14: The relationship between total released block volume for a statistical block model and joint set persistence for 3 joint spacings.
4.9 Constructing representative DEMs for case-study rockmass

The models that follow represent a first effort at completing the proposed tunnel characterization process from LiDAR data collection at the face and feature extraction, through to rockmass block model construction and analysis. The numerical models that have been presented thus far have been generalizations of the primary case-study rockmass. This section presents the best deterministic and statistical models for the case-study rockmass, based on the methods described previously and within the limits of 3DEC software, with some additional coding effort. The deterministic model is used to confirm the current failure mechanism and extent of failure. The statistical method, on the other hand, is used to assess the range of failure possible due to variations in current ground conditions.

4.9.1 Calibrating and validating with deterministic model

As discussed previously in Section 4.7.1, one of the primary advantages of the deterministic reconstruction is the ability to validate the model based on actual tunnel performance. By inputting joints actually exposed in the tunnel, the model can recreate the final tunnel geometry, post-block fallout and thus can be easily compared to final profile/geometry for validation. The rockmass model that back-analyzes the current ground conditions helps the tunnel engineer to evaluate his or her intuitive understanding of the mode of failure. Once the engineer has identified whether failure occurs by sliding in sidewall, wedge fall-out, etc., he or she can focus on identifying which joint orientations contribute to the failure.

The following deterministic model recreates the performance of the case-study rockmass in a 10 m diameter drill and blast tunnel at the Sandvika project site. Sliding failure in the left sidewall along tilted sedimentary bedding is the primary source of overbreak. This sidewall overbreak is seen in Fig. 4-15, an oblique view inside the LiDAR surface model. A comparison
between the actual tunnel performance and the 3D DEM is shown in Fig. 4-16. Figure 4-16A illustrates this same sliding plane in cross-section by slicing the LiDAR surface model. Figure 4-16B shows a photo taken at the face where the major sliding planes are still visible despite shotcreting. The DEM performs very comparably, as seen in failing blocks in cross-section in Fig. 4-16D and in a 3D view in Fig. 4-16D, where failed blocks are highlighted in magenta. The deterministic model performs as expected and replicates the actual failure observed in the tunnel. In this particular case, an average joint persistence of 0.58 allowed for the best match with actual tunnel behaviour. As described in Section 4.8.3.1, joints are sorted and assigned persistence gradationally.

Figure 4-15: Oblique view of the LiDAR surface model (viewed from the right side looking forward) with the major sliding plane in the tilted bedding rockmass highlighted (right sidewall is hidden from view).
4.9.2 Constructing a representative statistical model

Based on the validated deterministic model, the modeller can move towards an appropriate collection of statistical models that evaluate the range of behaviour due to variations in spacing, persistence etc. The presented models are based on the stereonet interpretation shown in Fig. 4-6. The four most critical joint sets were selected and have been modelled with interpreted spacing and persistence, two of which are prominent and the other two less so.

Spacing analysis was conducted as discussed in Section 4.5. For the statistical analysis, a “best” or most representative model is constructed based on the interpretation the modeller is most confident in. In addition to this, a suite of other models which investigate a range of rockmass parameters are also constructed. The work pursued looks at spacing and persistence, with a focus on persistence which is difficult to evaluate directly.

In addition to the procedures described in Section 4.6.2, geological interpretation was required in order to thoughtfully construct the model. For this particular model, the most prominent joint set (J1) falls along tilted sedimentary bedding. This had two consequences on model interpretation. Firstly, J1 was always input first into the model to reflect geologic history, which in the software used, made it a fully persistent joint set. The order of input is important. It can significantly affect rockmass performance. To test this, the order of input for the first two joint sets, with P=1 and P=0.7, was reversed. While the models had the same “average” persistence, the inverted model released between 7-50% of the block volume released by the original model, depending on joint spacing. The second significant geological interpretation is to ignore the minor variation in joint orientation that was documented in the joint set along bedding. It was felt that ensuring the bedding planes did not intersect each other was more representative of real rock conditions, than reflecting any local roll in bedding.
Figure 4-16: (A) Cross-section of LiDAR surface model with sidewall failure plane highlighted, (B) Photo at the face of 10 m diameter tunnel, (C) Cross-section of deterministic DEM with failed blocks in magenta (Average persistence= 0.58, moderate joint strength). (D) 3D view of DEM by showing sidewall failure
Statistical models should also be tested for the impact of geometry changes on block release, due to the way sets intersect. This can either be done by extending the tunnel model longitudinally or by moving seed points within a shorter model. For example, for the preferred statistical model of the case-study rockmass, the first joint set (J1) was shifted half a spacing (0.5 m) up and down to assess if this would alter block release. The results are shown in Fig. 4-17 where model B is the original and models A and C have their J1 shifted. Cross-sections of models A and C illustrate that the resulting sidewall failure can vary greatly, with all the same rockmass parameters, but with a slight shift in geometry. Model A is more representative of the significant sidewall failure documented at one tunnel face already seen in Fig. 4-15 & 4-16, while B and C are more representative of structural overbreak in typical tunnel sections. Of the statistical models tested, the model which best recreated observed tunnel conditions had an average persistence 68%.
Figure 4-17: The statistical model identified as being most representative of observed tunnel performance. A, B, C models have common setup parameters but vary only in the joint set J1 seed position. In A and C, the joint along bedding has been shifted up or down half the set spacing (±0.5 m).
4.9.2.1 Sensitivity study based on statistical modelling

As mentioned previously, statistical modelling is valuable in its ability to assess the impact of changing rockmass character to tunnel performance. For example, if larger rounds are proposed and more significant blasting contributes to increased joint persistence, it is useful to assess how increased persistence would affect stability in a representative rockmass.

Statistical models for the case-study rockmass were constructed with varying spacing (0.3-1.5 m) and persistence (for all sets). Fig. 4-18 visually demonstrates, via oblique views of two 3D DEMs, the range in failure in the right haunch that can occur within the range of tested spacing values. The graphical representations of the results are found in Fig. 4-19, showing quantity and total volume of released blocks. Fig. 4-19A shows a positively sloped trend between persistence and the quantity of blocks released. Models with tighter spacing have more removable blocks at the tunnel surface and thus release more blocks than wider spaced models for all persistence values. However, perhaps contrary to intuition and certainly contrary to assigned values in rockmass characterization schemes, the widely jointed models release a greater total volume of blocks. This study finds the conventional wisdom that tightly spaced joints lead to a less stable excavation is not necessarily always true for shallow tunnels. Rather, as seen in Figure 4-19A, for nearly all persistence values tested, the more widely spaced model released a greater volume of rock. This is visually confirmed in the examples of Figure 4-18: Figure 4-18A illustrates minor failure when there is tight spacing and moderate persistence while Figure 4-18B shows more significant block release in a model with wide spacing and full persistence (where “tight” spacing indicates a spacing equal to 3% of tunnel span, “moderate” spacing 10% of span and “wide” spacing 15% of tunnel span). In the models with tightly spaced joints, equilibrium could be re-established with the release of a few small blocks. However, in the widely spaced
models, equilibrium could only be re-established with the release of a few large blocks, causing significant overbreak and a greater volume of release. Thus, one might argue that the stability conditions created by the tightly spaced joint system are more favourable than those created in the rockmass with wider joint spacing. This is contrary to the ratings assigned in the rockmass classification systems that are consistently employed at rock excavation projects. Based on these significant findings, further investigation of rockmass behaviour in shallow tunnels in blocky ground should be pursued.

Figure 4-18: Two examples of statistical DEM for case-study rockmass. Magenta blocks having greater than 0.05 m displacement.
One important observation, visible in both Fig. 4-19A and Fig. 4-19B is that going from full persistence to somewhat discontinuous joints results in a large reduction in the number released blocks. The variation in block release within the range of more discontinuous joints (60-85%) is less substantial. This is consistent with recent discussion of rock bridges, where even

Figure 4-19: (A) Quantity of displaced blocks for 3 categories of joint spacing and for a range of joint persistence. (B) Total volume of displaced blocks for 3 categories of joint spacing and for a range of joint persistence.
small bridges can add substantially to joint strength. So, as Kim et al. (2007) suggest, simplifying joints to full persistence does indeed greatly overestimate the amount of rock requiring support. Another interesting observation is the significant deviation of the model with $P = 70\%$ from the trend of the widely-spaced models in Fig. 4-19B. The anomaly is likely a product of the added complexities of multiple joint sets in 3D. When fewer, but larger blocks are created, due to lower persistence and wide spacing, larger failed volumes may occur than those in models where more persistent joints create smaller blocks. Specifically in this case, the increase in total volume is likely due to the release of one or two large blocks, because no corresponding anomaly is captured in Fig. 4-19A. This documented divergence from trend reinforces the influence of geometry in rockmass block models and the need for many simulations in order to adequately characterize general rockmass behaviour. Thus the numerical values defining such curves are not transferable to other geometries or rockmasses, but unique to each simulation.

4.10 Observations and implications to rockmass modelling

As noted by Barton (1999), “the modelling of the components, rock, rock joints and discontinuities is far more logical and relevant than present black box continuum models”. Improving our ability to create representative discontinuum models rather than converting rockmass data to equivalent continuums further develops our understanding of actual rockmass behaviour. However, there remain obstacles to building these more “transparent” models. Barla and Barla (2000) identify two main challenges in building discontinuum models, the first being “the introduction in the model of those joints which are most critical to the response of rockmass”. LiDAR facilitates our ability to overcome this challenge. In the past, the inability to capture rock structure complexity in a practical way has discouraged the use of discontinuum modelling. When used, low levels of structural data impair the ability of discontinuum models to
be representative. However data collection tools like LiDAR, with proper interpretation, can improve modelling results and ease the reluctance of use. The additional structural inputs allow models to produce useful, reliable results rather than offering little added value.

While LiDAR-derived models may overcome some past challenges, limitations still exist, as discussed in Section 4.8. Bias has many repercussions on our ability to interpret data and so should be minimized as much as possible with careful data collection and later with judicious data interpretation as described in Section 4.8.2. Persistence, specifically our inability to accurately assess it either in the field or in LiDAR data at the office, requires special attention as a model input. This is emphasized by the dramatic range in behaviour for models with the same geometry but varying persistence (Fig. 4-11, 4-13, 4-14 & 4-18). As well, computer hardware limitations remain. Modellers may be deterred from discontinuum methods if they wish to create complex joint network models with deformable blocks and generally, if they expect the most representative models to provide results quickly.

4.11 LiDAR-integrated stability analysis and implications on support design

In constructing analogous deterministic and statistical rockmass models, tunnelling engineers can confirm failure mechanism, identify critical joint sets, calibrate persistence and test rockmass performance for a range of joint spacing and persistence values. The deterministic and statistical models play different roles. The deterministic plays more of a validation/calibration role that can then guide statistical modelling which can be used as a predictive tool for design of future tunnel sections.

By integrating LiDAR data into 3D block stability analysis, support design can be fine-tuned to actual rockmass performance. For example, one output of calibrated block models is the ability to assess size/shape of unstable blocks with a process such as that described by Kalenchuk
et al. (2006). The size/shape of blocks contributes to what type of ground control is most suitable, be it bolting, mesh or shotcrete. The anticipated block volume to be released, another output of these representative models, will dictate the required support capacity. When the rockmass performance is better understood, support does not need to be overly-robust in order to deal with risk. With more appropriate support, project costs can be minimized and the construction schedule can be reduced by the elimination of unnecessary support installation time. The flowchart presented below summarizes the process discussed in the paper, from data collection through to design outputs (Fig. 4-20).

4.12 Conclusion

This paper has proposed a workflow for integrating LiDAR-derived structural data into geotechnical tunnel analysis. The benefit of the increased ability to construct representative rockmass models is made evident by an improved understanding of the rockmass failure mechanism and sensitivities. In other words, it improves our ability to rely on discontinuum models for tunnel design.

The impressive quantity of data that can be extracted from LiDAR data allows the interpreter to more analytically consider significant rockmass characteristics such as persistence and spacing. These would otherwise be quick on-site approximations if anything. By creating a suite of models, the engineer has the ability to assess stability over a range of ground conditions and can assess the significance of any one parameter. This suite of models becomes a predictive tool for rockmass performance. Representative discontinuum models are a far more transparent method of stability analysis than simply assigning a rockmass rating or Q-value which cannot foretell the mode of failure or zone where the failure is concentrated. This additional information may facilitate zone-specific support in large excavations, which may lead to significant savings.
Figure 4-20: Workflow for integrating LiDAR data into 3D rockmass stability modelling
However, the presented research should remain a cautionary tale for use of emerging technology for geotechnical data collection. The overwhelming amount of data that can be extracted should not simply be used “as is”. If a representative rockmass is indeed the goal, data must be carefully interpreted and results calibrated based on site experience. Though LiDAR scanning might reduce the amount of time required at the face for structural data collection, this time should be reallocated to documenting other important information that will ease model calibration. This includes joint roughness and alteration, significant discrete features, apparent failure mechanisms and zones with greatest structural overbreak. Keeping in mind the limitations presented, the research demonstrates that creating representative 3-dimensional discontinuum models from LiDAR-extracted data is possible and can provide much insight to tunnelling engineers.

4.13 Acknowledgments

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Chapter 5

General discussions

5.1 Discussion

This chapter discusses the main findings of the research and their impact on future work seeking to integrate LiDAR into tunnelling projects. Key challenges encountered during the completion of this research are also addressed in this chapter, to a greater degree than was possible in submitted technical papers. Important next steps for future research in LiDAR applications for tunnelling are proposed. Finally, this chapter includes a more general discussion of how terrestrial LiDAR may be further integrated with large engineering projects.

5.2 Key findings and impacts

This thesis aimed to be very practical in nature and thus seeks to contribute to actual tunnelling practices. In the following sections, the findings of this research are presented in the context of how laser scanning technology has the potential to be integrated into tunnelling projects.

5.2.1 Practical use of LiDAR in an active tunnelling environment

The first key finding of the research presented in this thesis is that without any enhancements to available equipment, LiDAR scanning can be practically conducted at the face of an active tunnel, despite the constraints of the operational environment. Even with a simple tripod setup, the complete scanning process could be conducted during the allocated geotechnical evaluation time within the construction cycle. The success of field trials is encouraging to industry members, who might otherwise be hesitant to incorporate technology-driven alternatives.
into tunnelling operations. This hesitance is especially true for contractors, for whom misspent
operation time and cost is unacceptable. The ease of integration into the construction cycle has
been demonstrated and is necessary in order to justify further research that makes use of the data
collected.

5.2.2 Operational outputs are possible with minor effort

Another early finding of the research is that with minimal processing effort, tunnel surface models can be created and provide useful construction information for the contractor as well as document quality control for the project owner. Calculation of shotcrete thickness, as-built bolt density and overbreak analysis are all possible without significant processing, even in point cloud software more suited to other industries. These operational applications are significant because they provide immediate gratification for the LiDAR data collection and their value alone could justify the implementation of scanning at the face. With contractors/owners willing to invest in having the data collected, the data becomes available for geotechnical applications that require additional processing and interpretation effort for results.

5.2.3 Rockmass elements can be extracted and characterized

Furthermore, the research identified key rockmass elements that could be extracted from LiDAR data for use in rockmass characterization or later as numerical model inputs. This extraction requires additional effort and requires the interpreter to have both LiDAR processing skills and an understanding of geomechanical evaluation. Because of limitations in the data collected due to bias etc., special care must be taken. User interaction for feature extraction is recommended in order to obtain meaningful data. The implication of these findings is that LiDAR data has the potential to greatly enhance the way geotechnical data is currently collected. It can both confirm on-site assessments and provide complementary data for more detailed analysis.
Like any method of data collection, rockmass data extracted from LiDAR is not perfect. It is biased, based on where the data was collected from and is incomplete, documenting only what is exposed in the tunnel profile. Only with an understanding of these limitations should interpreters proceed with rockmass analysis. It must be emphasized that LiDAR data collection should not replace current on-site hand mapping. Traditional mapping is required for quality assurance and should be used to calibrate analysis that is based on LiDAR-extracted data.

5.2.4 LiDAR-extracted data enables representative discontinuum modelling

In addition to simply extracting the rockmass data from LiDAR data, this thesis explores the ability to create representative discontinuum models from the extracted information. Two unique methods of implementing the information in a discrete element model were identified and evaluated. A significant result of this research is that discontinuum models can benefit greatly from the additional data available. The enhanced rockmass database from LiDAR tunnel mapping can support the ability to use discontinuum models for back-analysis and forward prediction in tunnel design. With the data available from interpreted LiDAR data, modellers need no longer resort to “opaque” continuum models or discontinuum models relying on simplifications and assumptions.

5.2.5 Combined underground LiDAR workflow and integration into onsite engineering

Finally, this thesis discusses the ability to integrate LiDAR data collection, interpretation and use in stability analysis into current practices. It was found that despite using software not targeted to geotechnical applications, practical integration is possible and can potentially offer great benefit to project engineers. A more generalized workflow integrating the findings of Chapters 3 and 4 is found below in Figure 5-1.
Figure 5-1: Integration of LiDAR scanning for rockmass modelling and operational applications in drill and blast tunnels.

When the expertise is available and LiDAR documentation can be fully integrated into underground construction, geotechnical staff will have an improved understanding of project risk due to ground conditions. This is especially true with a large sequential excavation such as a
large-diameter cavern. Accurate documentation of discontinuity features in the first stages of excavation, as would be easily accomplished with LiDAR scanning and interpretation, is critical to identifying potential sources of future instability. Figure 5-2 shows the schematic of a cavern where a significant structural feature (fault) is documented by a LiDAR scan during the initial stage of excavation. The fault intersects a consistently spaced joint set, also retrieved from point cloud interpretation. With the orientation and position of the fault extracted from the LiDAR scan, projecting the fault into the rockmass above the second stage of excavation would be a simple task. This projection identifies a significant wedge risk. The size and volume of the wedge could be calculated in order to design appropriate rock bolt length and capacity. The ability to assess other discontinuities in space, relative to the fault, as the excavation progresses provides critical information about where structural instability should be expected and what support could mitigate it. Decker (2008) describes the use of LiDAR in a comparable way for a benched twin tunnel excavation.

![Figure 5-2: Schematic of how documentation of structural features in the first stage of a sequential excavation can be used to predict conditions in future stages. (Dashed discontinuity lines are interpreted, solid lines are observed).](image)
5.3 Challenges encountered during research

Because LiDAR has typically been used in the architectural, automotive and chemical industries, the workflow is not currently as smooth as tunnel engineers will eventually require. Several challenges remain to be resolved and are discussed in detail in this section. These challenges relate to the quality of LiDAR data, how we handle the data and the difficulties in associating the data to the results of traditional mapping methods.

5.3.1 Data quality issues

As should be the responsibility of any researcher, those developing LiDAR applications in the recent past have paid great attention to data quality. The primary observation of both Brunsdon (2009) and Habib (2009) is that LiDAR data collection is not perfect and the data is not without error, but LiDAR users should do their best to understand the sources of lost data and data error, attempt to minimize them, and use them in a way that best represents the original geometry. Buckley et al. (2008) describe various sources of error, which are added to initial mechanical error of the scanner. Buckley et al. then try to assign magnitudes of positional error that are the consequence of non-ideal data collection, global positioning data, processing etc. While the “error budget” shows much greater error values because it considers a long-range time-of-flight laser scanner (not a phase-offset scanner), this “budget” emphasizes that the cumulative pre-interpretation error can be substantial. Depending on the level of detail required, these error levels may become significant.

One might argue that, if the point cloud is dense enough for proper coverage, intensive quality checks are not required as long as the level of detail desired does not approach the level of scanner accuracy. This would be the case for mapping geological structure at the outcrop scale, the principal level of detail of the research presented in this thesis. However, if rockmass
characterization is to include an assessment of surface roughness, then point accuracy is of great
concern because small scale roughness is at the same scale as the scanner’s ranging error (mm).
In the case of roughness assessments, the cumulative error may be a decisive barrier to accurate
evaluations. The accuracy of raw close-range LiDAR data may be adequate for analysis at the
mm scale. However, more work is required to evaluate whether the errors introduced in the
integration workflow are significant enough to make the assessment of large-scale, but not small-
scale roughness, reasonable from LiDAR data collected in the field. It is due to additional control
in data collection that many attempts to characterize rock surfaces have been conducted in a
laboratory rather than in the field. However this is effort intensive and generally impractical as a
means of collecting information for engineering projects. The accuracy of scanners has improved
sufficiently that joint surface research can be undertaken in the field as long as quality assurance
measures are undertaken and checks on data quality are performed.

Methods of quality control (QC) have been proposed for airborne LiDAR data and some
show potential for verifying terrestrial data to be used in detailed surface analysis. Habib (2009)
explores internal and external quality checks that allow the data to be compared against data that
is similarly accurate or more accurate. The internal quality control methods employ the
comparison of two data sets of the same target from the same collection system from either the
same or a slightly different viewpoint. This would be practical for terrestrial data as long as the
two compared data sets are taken from nearby positions and have sufficiently large overlapping
areas. Of the internal quality control checks, the intensity return method, which compares the
interpolated intensity values on two surfaces (Habib 2009), is likely the least practical for
geological targets. The comparison of interpolated intensity images would not be effective for
rockmasses where intensity values vary within a small area (coarse-grained rock with minerals of
varying reflectivity) or where rock reflectivity is consistent and so has no distinct lighter or darker features to compare (massive fine-grained rock). A comparison of interpolated range would be better suited to assessing rock targets. However, Habib (2009) cites discontinuities as difficult to interpolate and thus a weakness of any interpolation-based method. This method would therefore have difficulty with a high relief, jointed rockmass. The comparison of linear features is not a likely candidate for QC of rock outcrop data because, as discussed previously, linear features are difficult to delineate without very high point density. Likely, the best approach for quality control of rock outcrop data is to check the coplanarity of conjugate planar patches in overlapping scans or by automated matching of original LiDAR data sets, methods proposed by Habib for airborne LiDAR data (2009). These methods compare detailed geometry rather than selected elements, such as linear features or intensity values, which are not necessarily detectable or consistently sampled in LiDAR scans of rock tunnels. The evaluation of conjugate planar patches would require user interaction to correctly select a sufficient number of matching patches while automated matching requires significant computational effort. External quality checks are another option entirely, where targets placed in the scan area are of known position. However, the major disadvantage of this method is that it requires an additional system such as a total station for external data confirmation.

Ranging error for the scanner used for this thesis (Leica HDS6000), according to calibration done periodically by the manufacturer, is cited to be at the sub-millimetre scale (0.6 mm). Despite the fact that the level of detail required is much less demanding than the tested accuracies, researchers using scanners with comparable accuracies still question the ability of the data to characterize joint plane orientation. This may expose an underlying distrust of LiDAR data, though perhaps justifiable considering that scanner calibration remains an opaque process,
contained within the walls of scanner manufacturers. Researchers have frequently invested substantial time in “validating” data by comparing joint planes extracted from the virtual rock outcrop to the orientation measurements retrieved by hand mapping with a compass (Lato et al. 2008, Mah et al. 2008, Bäcktröm et al. 2008). While it is important to compare new joint-mapping techniques to established methods, this type of exercise is in no way a means of quality control. This type of exercise assesses only whether or not the virtual joint plane evaluation meets current hand-mapping standards. In this thesis, the comparison between traditional joint data and LiDAR joint data was only employed to identify the differences in structural databases, but not as a data quality check. Comparing the datasets does not confirm how closely the LiDAR data truly represents actual outcrop geometry. The processes of selecting joints from the LiDAR data and taking a compass measurement on a small section of the joint surface introduce far more error than the scanner does. Indeed, Sturzenegger & Stead (2009) found that while compass mapping is susceptible to the waviness of a surface, this was not an issue for discontinuity orientation calculated from larger surface areas in the LiDAR data.

Based on the level of detail required for geologic structure mapping with LiDAR, the author suggests that quality checks are only required at the start of the project to confirm data reliability. For the remainder of the project, only consistent quality assurance procedures would be required. However, if detailed surface work is to be conducted, the author recommends that additional data quality checks should be implemented and an evaluation of total error post-processing should be conducted. As long as special attention is given to data quality, the author feels that LiDAR data will enable further developments in rock surface characterization and facilitate great contributions to our understanding of how joint strength and roughness/surface geometry are related.

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5.3.2 Current software and processing challenges

Because of the high computing demands of LiDAR data, several challenges due either to software or hardware capabilities, restrict the ease with which this technology can be integrated into engineering projects. The sources of greatest frustration in handling LiDAR data include: the large file sizes, 3D nature of the data, incompatibility of file types and the user’s requirements for viewing and manipulating the data at a practical rate. The size of file, as mentioned previously, can be up to several GBs in size. In order to be able to load and process this size, hardware requirements are significant. A substantial amount of memory and multi-core processing ability are recommended. For the work of this thesis, a double quad-core computer with 16 GBs of RAM was used. However, this did not provide significant benefit in all stages of data processing. Only some of the processing functions in the PolyWorks software are multi-core enabled. Software developers are working to improve this, but the urgency with which they work is a function of the demand for manipulating very large datasets. To the detriment of industries only beginning to integrate LiDAR technology, the software developers’ priorities are to serve their larger, more established markets (automotive, chemical).

Another challenge is that each scanner manufacturer and software provider has their own proprietary file formats. The challenge with this is that certain software is more or less suited to particular tasks, be it viewing data, meshing, identifying geological features etc. and it becomes difficult, if not impossible, to take advantage of their various strengths if the file formats are not recognized between them. For example, in this research point cloud data collected from a Leica scanner could be viewed in Leica’s Cyclone program, but not well meshed. In order to use Polyworks’ powerful meshing algorithm, files have to be transferred in raw form. However, due to incompatibility issues, the point intensity values could not be viewed in PolyWorks, making
viewing less functional. In the future, users must demand that point cloud software tools have the ability to handle diverse formats or a movement to standardize data types will be necessary.

One of the abilities that determine if software can more or less adequately handle underground datasets is the ability to handle fully 3-dimensional data rather than 2.5D, as mentioned previously. Some meshing algorithms are only suited to 2.5D datasets. While this limitation was not a problem for past geological applications, namely slopes, these meshes cannot be used if complete tunnel models are to be created. This was the primary set-back of Split-FX (Split Eng.). This software was designed to be able conduct geo-structural characterization and directly transfers selected discontinuity plane data to stereonet projection, a very useful function, but it cannot mesh more than one tunnel plane at a time (wall, face or back).

An additional challenge with this software is the automated patching algorithm used to identify joints. As presented in Section 2.5.1, Split-FX has been shown to provide good joint delineation for blocky rock outcrops but more complicated surface patterns, as seen underground where the rock surface is also a function of blasting and scaling, remain challenging to the automatic patching algorithm. At this point, it was deemed that interactive joint selection provided the best data sets. While automation algorithms may improve, the author feels that some level of user interaction should remain in order to provide the opportunity to interpret between natural and induced fractures. However, in order for structural characterization to be practical on a regular basis, this process needs to be streamlined. Perhaps, a semi-automated process, similar to that in 3G’s JointMetriX photogrammetry software, is ideal (2006). The user clicks on the joint plane and this point acts as a seed for the automated plane identification algorithm, which extends the plane as long as the surface remains planar.
The fact that many independent research groups have tried to develop their own software to do geotechnical interpretation on LiDAR point clouds underlines the fact that there are no adequate programs available that unite the computational needs and the industry-specific functionality. There are two ways that point cloud software can meet the forthcoming needs of geotechnical engineers. Either a powerful, standard LiDAR processing software, i.e. PolyWorks, will begin to cater to the more specific needs of less prominent engineering disciplines, working with industry experts to develop the functions required, or point cloud software developed especially for geotechnical applications will be further refined including an investment in coding expertise to acquire more robust meshing and patching algorithms. A software development that unites the computational needs and the industry-specific functionality, as has emerged for photogrammetry data, is necessary for future industry acceptance of the technology.

5.3.3 Measurement methods of rockmass character

Based on its development, rockmass characterization has come to adopt a very qualitative language. This qualitative language is hard to coordinate with the very quantitative nature of numerical modelling. While “very blocky” may adequately describe a rockmass qualitatively, many numerical values will be required to represent this in a model (joint density, rockmass stiffness). This translation of rockmass terminology becomes even more complex when LiDAR interpretation is incorporated. If the LiDAR interpreter/geotechnical engineer wishes to create representative rockmass models, there are three languages that he/she must speak: 1) information that is measurable in LiDAR data, 2) descriptors used in traditional rockmass classification, and 3) the values required as inputs in numerical models. The ability to create representative numerical models is a function of speaking each of these languages, translating between them, and ensuring that each language is appropriately conveying actual rockmass character. Roughness
(joint surface character) and persistence illustrate the complexity of these translations. Roughness is a function of 3-d surface geometry that can be captured by LiDAR data, and yet current rockmass characterization typically assigns qualitative terms such as “rough and planar”, or at best uses 2D profiles to obtain a JRC value (Barton & Choubey 1977). However, in numerical modelling, this key parameter is communicated via assigned shear strength values which are typically determined from empirical relationships. Even more challenging is the translation of persistence, which is not incorporated in traditional rockmass assessment schemes despite its significance. LiDAR may be able to make an estimation of persistence by evaluating diameter of exposed joint surface, but this has yet to be developed. In addition to this, the methods of incorporating persistence into numerical models are vast (discs, percentage of cuts etc.). In keeping with the analogy of language, there are many persistence dialects. This inability to correlate the data we can collect (LiDAR), the information we typically record (rockmass classification) and the data we use to construct models is a challenge that must be faced in order for future numerical modelling work to truly benefit from the increased ability to document the rockmass that LiDAR provides.

5.4 Future areas of research

This thesis serves as a primary exploration of LiDAR applications to tunnelling. Based on the findings of this research, there exists the opportunity to improve the methods of processing and rockmass data extraction as well as to improve the quality (representativeness) of resulting rockmass models.

Future research should seek to improve the number of rockmass character parameters that can be extracted. As has been discussed, the assessment of persistence remains a significant challenge. LiDAR documentation of the tunnel face offers the unique opportunity to assess
exposed joint surface area. This should be evaluated as a method of estimating joint persistence.

In general, rock mechanics still does not have firm understanding of the contribution of persistence to rockmass stability. In documenting joint surfaces and tunnel performance, future work with persistence may offer great benefit.

In addition to persistence, joint surface geometry should be further investigated. The evaluation of large scale roughness via 2D profiles has been demonstrated, but the nature of LiDAR data provides the opportunity to evaluate the surface in three dimensions and this should be pursued. While intensive efforts of this have been conducted by highly accurate systems in labs, the opportunity to do this in the field is only recently practical. As discussed in Section 5.3.1, the scale of joint roughness is at the boundary of the LiDAR scan accuracy and so data should be approached cautiously. Quality control and careful use of meshing algorithms will be required for the future evaluation of roughness with LiDAR data.

As discussed in Chapter 4, bias remains a significant issue for those who must interpret the extracted structural data. Research aiming specifically to assess bias associated with LiDAR data collected in the tunnel environment should be pursued, paralleling the work completed by Lato for bias in rock slope data (2010).

Following the success of Chapter 4 in the creation of rockmass block models, further research should seek to implement the proposed workflow. Further refinement of the rockmass reconstruction methods will be possible with the experience of different rockmasses and tunnelling projects. Further, more sophisticated fracture network models should be introduced into the workflow. Without the limitations of the joint cutting model included in 3DEC, more representative reconstructions for different rock types may be possible. More complex joint
configurations, as used in reservoir modelling, are available in programs such as FracMan (Golder’s Associates).

There exists great potential to better understand tunnel performance if LiDAR documentation and subsequent stability analysis are executed at many tunnelling projects. A better understanding of tunnel instability due to geologic structure will be possible. With a parametric study of many LiDAR-documented tunnels, certain rockmass elements such as persistence may be better understood. The results of sensitivity studies in this research reveal that current classification systems may not accurately assess rockmass behaviour in blocky ground, specifically the relationship between joint spacing and intensity of tunnel overbreak. In the long-term, studies in rockmass reconstruction and sensitivities of tunnel stability may help revise current rockmass characterization schemes and better calibrate empirical design methods.

The ability for the proposed workflow to be adapted to mechanized tunnelling projects has yet to be demonstrated. With a growing number of tunnelling projects using tunnel boring machines (TBM), it would be desirable if the techniques developed in this thesis were transferrable to a different data collection environment. Major challenges in scanning at TBM operations are: obstruction of the face by the cutterhead, shadowing of sidewalls due to support installation equipment, and the smoothness of tunnel walls following excavation. While the sidewalls are exposed during excavation, prior to liner installation, there may be little structural information available for documentation because unlike after blasting, rock discontinuities are less likely to define the excavation boundary. Documentation of the face may be possible if the TBM pushes back and the LiDAR scanner is placed ahead of the cutterhead. However, the ability to collect any meaningful data may be ruined by the overprinting of cutter damage to the rockmass in the process of excavation. Due to these limitations, the use of LiDAR in TBM
tunnelling will likely be restricted to operational applications, such as shotcrete thickness, that do not require the exposure of geo-structural features. As well, due to the significant vibration caused by the operating TBM, LiDAR scanning would only be practical during maintenance shifts when the TBM is not in operation.

5.5 Future application of terrestrial LiDAR to engineering projects: models to follow and challenges ahead

As discussed in Section 5.3, there remain several challenges that must be surmounted in order for there to be a fluid integration of LiDAR documentation into the tunnelling design and inspection process. Nonetheless, there remains great potential for LiDAR applications in underground rock engineering to move beyond the interpretation of surface models as developed in this thesis. In converting LiDAR scan data into highly accurate, detailed as-built CAD (computer-aided design) models, the potential of future tunnelling applications is amplified. For example, tunnel engineering firms have begun to collect LiDAR data of completed tunnel sections to document modifications due to unexpected ground conditions or changes made by the contractor on the job. CAD models that document the final as-built tunnel will be helpful with contract verification, maintenance of utilities, later retrofits and monitoring. These models could be used in settling claims as well as in hopefully preventing claims by helping parties to agree on ground conditions and completed work. If the ability to visualize and manipulate these models in real-time was also possible, the LiDAR-based CAD models could become an impressive engineering tool, allowing engineers to assess details critically and interactively. Unlike drawings, these models would allow the users to add/subtract layers and components in real-time and understand the 3D interaction of complex systems. Outside of design applications, virtual
reality (VR) environments created from these complex CAD models would be useful for site orientation, briefing external specialists and communicating information to the public.

In addition to the challenges already present, real-time visualization and manipulation of large data sets remain the primary roadblock to future applications such as these. Research groups have sought to develop software platforms that can both handle large datasets and visually interact with them at practical rates. For example, Environ seeks to integrate the wealth of data and complexity in CAD models into a format that can be visualized in real-time for applications such as design-review, maintenance, and health, safety and environment simulations for oil and gas industry facilities (Raposo et al. 2009). One significant observation of Raposo et al. (2009) is that the better we can visualize as-built data or simulation results, the better we, as engineers, can critically review it. This is an important motivation of developing real-time visualization capabilities for engineering models. With many complex numerical simulations using “black-box” processes, the ability to ensure that results are realistic is important.

One consistent theme in the literature is that the operations we wish to execute often surpass the capabilities of current hardware (ex. memory, graphics cards). Up to now, the primary way of dealing with hardware limitations is to simplify, though this can often lead to a loss of detail. If one of the primary advantages of collecting LiDAR scans is their detail, then these limitations must first be resolved before we see the full benefit of the data. Processing power and memory limit how much data we can visualize and how fast we can load/manipulate large files such as LiDAR scans or intricate CAD models. As we wait for further hardware development, software developers must figure out the best ways to organize or work with the data. Bruderlin et al. discuss this in depth in the context of complex CAD models (2007). The platform they develop, “Interviews3D”, proposes that the best way to deal with this challenge is a prioritization
of the data to be loaded and viewed (Bruderlin et al. 2007). By using what they call “visibility-guided rendering” (VGR), not all of the model has to be loaded in order to view it from a particular perspective and thus makes the process more efficient. As well, moving from one view to the next is made more efficient by assuming that only a small percentage of data loaded has changed. Furthermore, the program operates on a “level-of-detail approach”. This will be a very important principle for future developments in engineering model visualization in order for detailed databases to be practically integrated into design processes/construction evaluation etc. However, making viewing more efficient does not necessarily make data processing more efficient, where all data, even that which is not visible from a given viewpoint, is required for computations. Processes such as alignment, geo-referencing and surface model creation in LiDAR data processing will continue to be computationally intensive. Models could however be simplified for some of these processes by replacing point cloud data with representative primitives. The development of feature recognition and primitive fitting is required in order to better suit the needs of the now diverse group of industries using LiDAR. This will be a challenging undertaking as the features requiring representation in geotechnical applications will not necessarily be as distinct as pipes and valves, which are typical primitives currently available in point cloud processing software. Research continues in this field. In summary, high complexity as-built CAD models based on data extracted from LiDAR scans will have great application to engineering projects. If these models can be visualized in real-time, engineers will be able to interact with their designs and completed work in a novel way. Many software/hardware challenges exist, however, and need to be overcome so that the integration process does not instead make the engineering design/evaluation process less efficient (time spent in processing, file conversion, slow manipulation etc.).
Chapter 6

Summary and conclusions

6.1 Overview of research objectives

The research included in this thesis addresses a collection of objectives related to the practical employment of LiDAR in the active tunnelling environment. Once it was demonstrated that data could be collected in practical manner, research efforts focused on what information to extract and how to apply it. Applications of the data to construction management (operational applications) as well as geomechanical characterization were fully explored. The techniques used in assessing rock slopes provided guidance for the work, but a critical eye was required because new challenges, particular to the tunnelling environment, arose. The proposal for a workflow to integrate the use of this technology into geotechnical engineering in the underground environment represents the cumulative achievement of the pursued research objectives.

6.2 Summary of work

Rather than refining a pre-established process, this research is innovative in nature and thus seeks to explore a broad range of topics. This thesis explored a diverse array of LiDAR applications for the underground environment in order to assess their potential. The three sections below summarize the achievements of the primary limbs of presented research.

6.2.1 Practical employment of LiDAR in the active tunnelling environment

The demonstrated ability to collect LiDAR data at the face of an active drill and blast tunnelling operation without disrupting the excavation cycle represented an important first achievement in this thesis. Had this objective not been accomplished, the achievements of later work would be greatly undermined because few contractors would ever agree to future research.
knowing that their budget/timeline would suffer. Field trials were conducted at two railway tunnel project sites, including 5 tunnel headings (10-15 m in diameter). This work found that scanning at the face could be completed in less than 5 minutes using a static tripod setup (with data download upon returning to the office).

6.2.2 Diverse operational applications and ability to extract meaningful rockmass information

Once data had been successfully collected at the face, the range of information extractable from the LiDAR scan was assessed. The author found that there were many applications of interest to the contractor or on-site engineer including: excavation geometry, final liner geometry, shotcrete thickness, overbreak analysis, installed support verification, assessment of scaling and leakage zone evaluation. With respect to rockmass characterization, an equally impressive list of attributes could be extracted from the data including: joint orientation and position, discrete discontinuities across several faces, joint set spacing and large-scale joint surface characterization. The limitations and challenges associated with the extraction of this information were evaluated. Some challenges are associated with deficiencies of the data itself (bias, occlusion), while others are associated the shortcomings of point cloud software for geotechnical applications.

6.2.3 Practical integration of LiDAR into complex rockmass modelling

Based on the successful extraction of elements of rockmass character, the research incorporated this information into discontinuum modelling with the aim of constructing more representative rockmass models than have been possible from traditionally collected geostuctural data. Two primary methods of rockmass reconstruction were developed and evaluated: deterministic and statistical. Deterministic reconstruction was found to be most appropriate for
back-analysis, for confirming mode-of-failure and for calibrating persistence and strength parameters. Statistical reconstruction was found to be superior in predictive modelling for design of future tunnel sections as well as sensitivity analyses. Both methods were validated by comparison with actual tunnel performance in one section of the case-study tunnel.

The greatest triumph of this thesis was the demonstrated success of the complete workflow for the integration of LiDAR scanning into the stability analysis of rock tunnels. While the streamlining of processing and data extraction will be required to make the method more attractive to the average contractor/tunnel engineering firm, the use of LiDAR underground has been found to have great potential for future tunnelling projects. Further, numerical modelling based on the data extracted from tunnel scans has the potential to expand the industry’s understanding of blocky rockmass behaviour underground.

6.3 Contributions

The research included in this thesis has been the source for several publications and presentations. Research has been targeted to both the tunnelling industry as well as the general rock mechanics community. A full list of the contributions resulting from this research is presented below.

6.3.1 Articles published in refereed journals


6.3.2 Fully refereed conference paper and presentation (abstract and paper are refereed)


6.3.3 Partially refereed conference paper and presentation (abstract is refereed)


6.3.4 Refereed extended abstract and conference presentation

6.3.5 Courses given


6.4 References


Itasca Consulting Group. 1998 Minneapolis, MN, 3DEC, vers. 3.00.


Appendix A

3DEC code for rockmass stability analysis

This appendix includes the code run in Itasca’s 3DEC program for the construction of the rockmass models and stability analysis. The example provided is for a statistical reconstruction. For a deterministic reconstruction, the only substitution would be inputting a list of all the discrete joint planes instead of statistically-described joint sets. The rockmass stability is evaluated by counting the number of rock blocks released into the tunnel and their volume. Blocks “released” were defined numerically as having a total displacement greater than 0.05 m.

1. Set up rockmass model and excavate tunnel

poly brick -10 10 -5 20 0 10
Mark region 1
hide

poly brick -11 -10 -5 20 0 10
poly brick 10 11 -5 20 0 10
poly brick -10 10 -6 -5 0 10
poly brick -10 10 20 21 0 10
poly brick -10 10 -5 20 -1 0
poly brick -10 10 -5 20 10 11
mark reg 3
fix reg 3

seek
hide reg 3

prop jmat 1 f 60 co 1e10 t 1e10 kn 1e11 ks 5e10
prop mat 1 dens 2600
tunnel a 5,0,-10  5,5,-10  4.6194,6.91342,-10  3.53553,8.53553,-10  1.91342,9.6194,-10  
-1.82347e-016,10,-10  -1.91342,9.6194,-10  -3.53553,8.53553,-10  -4.6194,6.91342,-10
-5,5,-10 -5,0,-10 &
b 5,0,20  5,5,20  4.6194,6.91342,20  3.53553,8.53553,20  1.91342,9.6194,20  
-5,5,20 -5,0,20 &
region 2

set atol 0.001

;insert joints into model, statistical reconstruction
jset d 61 dd 72   s 1 0.2 o 0.2,7.2,5.25   n 250 ;set J1
pause
jset d 88 4.5   dd 175 4.5   s 1 0.2     o 0.2,9.42,5.25   n 100 p 0.7 ;Set J2
pause
jset d 25 12.5    dd 32 12.5     s 1.5  0.5   o 0.2,9.42,5.25  n 50   P 0.5 ;set J3
pause
jset d 49 31.7  dd 288 31.7  s 1.5  0.5  o 0.2,9.42,5.25   n 50 p 0.5 ; set j4

save setA_P3-setup.sav

;apply insitu stresses and gravity
insitu stress  -0.75e6  -0.75e6  -0.75e6 0 0 0
gravity 0 -10 0

hist unbal
cycle 500 ;reach equilibrium with solid rockmass

remove re 2 ;excavate tunnel
cycle 500 ;reach equilibrium with excavated tunnel, very strong joints

;progressive reduction of joint strength to not "shock" system
prop jmat=1 f 55 c 1e8 t 1e8 kn 1e11 ks 5e10
change jmat=1
cycle 200
prop jmat=1 f 50 c 1e7 t 1e7 kn 1e11 ks 5e10
change jmat=1
cycle 200
prop jmat=1 f 45 c 1e6 t 1e6 kn 1e11 ks 5e10
change jmat=1
cycle 200
prop jmat=1 f 40 c 5e5 t 5e5 kn 1e11 ks 5e10
change jmat=1
cycle 200
prop jmat=1 f 35 c 3e5 t 1e5 kn 1e11 ks 5e10 ;c = 300 kpa t = 100 kpa
change jmat=1
cycle 200
prop jmat=1 f 30 c 1e5 t 5e4 kn 1e11 ks 5e10
change jmat 1
cycle 200
prop jmat=1 f 30 c 1e5 t 0 kn 1e11 ks 5e10
change jmat 1
cycle 200
prop jmat=1 f 25 c 1e4 t 0 kn 1e11 ks 5e10
change jmat 1

2. **Run stability assessment**

cycle 60000 ;or as long as needed until unbalanced forces remain constant.

3. **Assess rockmass stability**

;identify blocks which have a displacement > 0.05 m
def block_vol

array bb(10000, 3)
array cc(10000,3)
cc(1,1) = string(cycle) + ' steps'
r=0
bi = block_head
loop while bi # 0
command
mark block bi displacement 0.05 region 4 ;mark it re 4 for failed
endcommand
If b_region(bi) = 4
if b_vol(bi) # 0 then ; and volume not zero
r= r + 1
bb(r,1) = r
bb(r,2) = bi
bb(r,3) = b_vol(bi)
cc(r+1,1) = string(b_vol(bi))
endif
endif
bi = b_next(bi)
endloop
volcalc
printme
end
def volcalc
volc= 0
loop mm (0, r)
    volc = volc + bb(mm, 3)
endloop
end

def printme
ii=1
loop while ii< r+1
    oo= out( string (bb(ii,1)) + ' '+ string (bb(ii,2)) + ' '+string (bb(ii,3)) )
    ii=ii+1
endloop
i0= out('Current failed total volume is ' + string(volc) + ' made of ' + string(r) + ' blocks')
c(r+2,1) = 'current failed total volume is' + string(volc) + ' made of' + string(r) + ' blocks'
end

4. Create a file to view data

def setup
    a_size = 20
    to_read = 0
    to_write = 1
    to_fish = 0
    to_ascii = 1
    filename = 'seta_p3-results.dat'
end
setup

def fileme
    status = open(filename, to_write, to_ascii)
    status = write (cc,r+1)
    status = close
end
fileme