Geotechnical applications of lidar scanning in tunnelling

S. Fekete, M. Diederichs & M. Lato

Queen's University, Kingston, Canada

ABSTRACT: Lidar is a remote sensing technology has been used to model geometry in a wide range of industries due to the high resolution 3-dimensional 'point clouds' produced. Advancements in the rate of laser scanning as well as increasing robustness and portability of the systems in recent years have been sufficient to encourage its use in more hazardous and dynamic environments. Researchers from Queen's University, Kingston, have demonstrated the practical employment of successive tripod set-ups within the normal excavation cycle at a drill and blast tunnelling operation near Oslo, Norway. The use of these data sets shows much potential for geotechnical applications, both for operational/contractual information as well as geo-structural data. Operational or contractual information obtained includes: shotcrete thickness, support quality control and leakage behind the lining. Geomechanical interpretation of the tunnel lidar scans can provide: joint set orientation and spacing, structurally controlled overbreak geometry, joint roughness and identification of discontinuities visible as lineations in successive rounds.

1 INTRODUCTION

Safety, long term stability and quality control in modern tunnelling operations all demand the acquisition of geotechnical information as well as excavation and support data as the tunnel face progresses. Operational constraints in tunnel construction, however, demand the implementation of fast and effective technology to achieve this goal. The use of high definition 3-dimensional laser scanning (lidar) in a tunnel environment demonstrates great potential for this application. In principle, the scanners transmit and collect laser pulses that are reflected off objects, recording the location of millions of physical points in space. The ‘point cloud’ generated is a high resolution 3-dimensional dataset of the scanned scene. Normally, the point data (x,y,z,i) also includes a reflection intensity value(i). These data sets can be manipulated with various software applications in order to create realistic and practical surface models.

Applications of the technology span many industries including architecture, crime scene investigation, art preservation, transportation infrastructure maintenance, open pit mining and geo-hazard mitigation. Static systems have traditionally been employed for parts manufacturing inspection as well as chemical plant design and maintenance. The geological engineering community uses lidar for landslide monitoring and more recently, rock outcrop characterization, rockfall hazard assessment and stratigraphy modeling (Bitelli et Al. 2004, Kemeny et al. 2006, Strouth & Eberhardt 2005, Buckley et al. 2008).
The application of laser scanning in underground excavations has been increasing in recent years. Laser profilers, like the Zoller + Fröhlich Profiler6000 or the Bever 3D Profiler, have been in use for more than twelve years and produce conical data sets useful for as-built tunnel profiles (Fröhlich & Mettenleiter 2004, Bever Control 2009). Currently, 3-dimensional laser scanning in tunnelling has been primarily used to create as-built final lining models for construction quality control. 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 system by Laser Geomatics (Jackson 2008). There have also been examples of laser scanning used to evaluate rock or liner deformation in tunnels (Van Gosliga et al. 2006, Lemy et al. 2006). An example of a lidar point cloud model for a completed unlined test tunnel in Oslo (Bankal site) is seen below in Figure 1. The full model is the product of 11 aligned (registered scans).

![Figure 1](image1.jpg)

Figure 1. (upper) 3-dimensional point cloud: 11 aligned scans, med. resolution; (lower) View of lidar point cloud data from inside model, with point of view indicated above, Bankal tunnel, Oslo.

The employment of a static lidar scanner for geotechnical assessment in a drill and blast tunnel operation has been demonstrated at the Sandvika railway tunnel site near Oslo, Norway through a collaborative project involving Queen’s University (Kingston, Ontario) and the Norwegian Geotechnical Institute (Oslo). Two additional sites near Oslo were used to model completed unlined tunnels (Akershus railway tunnels and Bankal test tunnel). This paper will explore the application of static lidar scanning for geotechnical assessment. The applications to be discussed, as well as the parties to most directly benefit, are found in Table 1.

Table 1. Geotechnical 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>
<tbody>
<tr>
<td>Application</td>
<td></td>
<td></td>
</tr>
<tr>
<td>As-built tunnel model</td>
<td>Contoured shotcrete thickness</td>
<td></td>
</tr>
<tr>
<td>As-built bolt spacing</td>
<td>Potential leakage mapping</td>
<td>Structural discontinuity geometry</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Structural overbreak analysis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surface characterization</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Feature mapping across faces</td>
</tr>
</tbody>
</table>
2 LASER SCANNING TECHNOLOGY AND TUNNELLING

2.1 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. Lidar scanners function independent of underground lighting conditions as the laser is its own "light source". In the past, the use of lidar in active tunnels has been impractical due to long scanning times. However, the development of portable, high-speed phase-based scanners now allows for their use in active tunnels.

2.2 Data collection in and operational environment

The authors used a stationary tripod setup for the Sandvika tunnel investigations to scan the face, walls and crown after each round. During this demonstration phase, three headings (two 10 m diameter and one 15 m diameter) were scanned at multiple face positions. The scans were conducted after blasting, mechanical scaling, and manual scaling. The scanner was set up just inside the limit of supported rock, for safety and best scanning practice, approximately 7 m from the face (0.5 to 1 diameter from the face is optimal). Set-up, scanning and take down could be completed in 5 minutes for each round. In this way, scanning did not disrupt excavation work flow. 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. The rigorous mechanical scaling did however greatly damage the blasted rock surface. It was noted in the field that some of the geologic structure was obscured by scaling marks. The ability to identify rock mass discontinuities can be improved if scanning is performed before mechanical scaling; the trade-off is that pre-scale data underestimates actual shotcrete thickness.

Scans were performed with the Leica Geosystems HDS6000, a phase-based scanner with a maximum range of 79 m at 90% reflectivity (Leica Geosystems AG 2008a). 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. The system provides high speed, high density acquisition at up to 500,000 points per second. An image of the tripod setup at the Sandvika tunnel site is found in Figure 2.

![Figure 2. Lidar tripod set up at 10 m diameter Sandvika tunnel near Oslo, Norway.](image)

3 DATA PROCESSING

The large data sets produced in laser scanning (up to several GB in size) require several processing steps before they can be analyzed and interpreted. The procedure can be simplified into the following steps:
i Reduce data set to region of interest (ROI) or decimate data overall
ii Create surface model (mesh)
iii Align with adjacent scans, if desired
iv Measure/interpret

The data set can be edited to only include the ROI and remove any unwanted objects: scaling equipment, muck piles etc. The reduction of data helps with managing the large file size. The alignment procedure is required in order to connect scans and create full tunnel models. The creation of the mesh or surface model helps reduce 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. As well, the mesh often improves the interpreter's ability to visualize the data. The process of reducing the point cloud to a mesh in order to create a 3-dimensional tunnel model is illustrated below in Figure 3.

Figure 3. Point cloud processing: a) Raw point cloud b) Triangular mesh, and c) Meshed tunnel model

Various software programs can be used to view, align and model point cloud data. For this project, Cyclone and Polyworks (Leica Geosystems AG 2008b, Innovmetrics 2008) were used. The alignment of three 5 m rounds at the Sandvika site is shown in Figure 4. The ability to analyze and interpret the data is a function of data quality, program functionality and also computing power. A processing challenge specific to the tunnel environment pertains to the complexity of the mesh generation algorithm; the mesh is required to be fully 3D rather than 2.5D as provided by meshing algorithms of some software. Various processing and interpretation functionality has become automated and incorporated into point cloud software, however, it must be stressed that there remains a requirement for constant quality control by the interpreting geologist or engineer.

Figure 4. Alignment of three 5 m rounds of an advancing drill and blast tunnel, meshed model, Sandvika
4 GEOTECHNICAL APPLICATIONS

By aligning active face scans, high density 3-dimensional models can be obtained that unite information from before and after support installation for rockmass assessment as well as support quality control tool. Various applications of lidar scans to tunnelling are presented below.

4.1 Geological Structure identification

A high resolution scanner can return very sensitive intensity values in addition to point cloud location information. While this data can be combined with pixel colouration from an accompanying visual light based camera image, the intensity data from the laser itself is often sufficient to effectively record geological structure of concern as shown in Figure 5.

Figure 5. Continuous structure (arrow) identified in raw laser intensity data (Fossvein site).

4.2 Shotcrete thickness verification

The advantage of 3-dimensional scanners over laser profilers is the density of data obtained. When lidar data after liner installation is compared against the original blasted rock surface, shotcrete thickness over the whole surface can be calculated. In Figure 6, the calculated shotcrete thickness of a 5 m length of tunnel is shown, where green-blue regions are those where shotcrete is greater than 10 cm thick and regions in red are below 5 cm in thickness.

Figure 6. Meshed tunnel model showing shotcrete thickness for 5 m round - Sandvika site
4.3 Support installation verification

Quality control of support can also include bolt installation as well as other support audit functions. Data collected during the construction phase can also be analyzed for potential prevention of leakage or shotcreted tunnels can be scanned to identify new or persistent leakage zones (possibly related to geological structure. This ability to differentiate dry from moist shotcrete may be useful in identifying key (open or pressurized) structural discontinuities now obscured by the liner. A 40 m length of tunnel illustrates the contrast of intensity for wet and dry shotcrete where moisture due to bolt installation is pronounced (Fig. 7).

Figure 7. Raw point cloud data where wet and dry shotcrete zones can be identified in comparing intensity values, Sandvika site

4.4 Structural discontinuity evaluation

Of the time a geologist or geological engineer spends at the face, a large portion is dedicated to mapping structural discontinuities. 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 filling.

Discontinuity analysis using lidar data has many advantages over traditional tunnel mapping as discussed by Decker (2008), which include permanent digital rockmass documentation that can be reinterpreted by other specialists as well as an increased quantity and accuracy of measurements with less time spent at the face/in hazardous zones. Further, the scanning and alignment of subsequent rounds can be used to create more extensive rock mass models, enhancing the ability to identify critical discontinuity features. Geo-structural analysis of rock slopes with lidar data has been successful (Lato et al. 2008) and a similar approach can be applied to the tunnelling environment.

4.4.1 Discontinuity geometry

Discontinuity extraction from point cloud data can be done either interactively or automatically. Figure 8 below shows a 15 m length of exposed rock, three rounds of excavation, with 158 joint measurements extracted interactively by fitting planes to joint surfaces. Figure 9 shows the stereonet plot of the resulting planes in Dips (Rocscience 2006). The results of traditional mapping, i.e. by hand with compass, and interactive mapping of the lidar data are found to be very comparable.
Automated feature extraction is attractive in its ability to 'objectively' detect discontinuities. However, the authors find that for the tunnel environment, especially where the rock face has been damaged during excavation, current automated feature extraction does not provide acceptable structural information. The results of automated joint detection algorithms are either noisy, causing any significant structural information to be masked, or too filtered and allow for a lot of lost information. For this reason, the authors have only presented the results of manual feature extraction.

The extrapolation of smaller joint features into the rockmass can be useful for identifying joint spacing, potential locations of wedge failure as well as the prevalence of random joint orientations. Figure 10 illustrates extrapolation of joints for three 5 m rounds of a 10 m diameter tunnel, where features with similar orientation are colored the same and random orientations remain in grey.
4.4.2 Discontinuity spacing

The advantage of 'virtual' structural mapping extends beyond feature orientation and offers an easy assessment of discontinuity spacing. Figure 11 below illustrates one major joint set in the wall of a 10 m diameter tunnel and the joint spacing distribution obtained from the data.

4.4.3 Surface characterization

The high density of lidar data allows for detailed analysis of joint surfaces themselves. Research in past years has attempted to both correlate profiles extracted from 3-dimensional surface models to current 2-dimensional profile characterization like JRC (Barton & Choybey 1977) as well as, to create new 3-dimensional fracture models (Haneberg 2007, Rahman et al. 2006, Fardin et al. 2001). Research is ongoing in this area. Large scale roughness is distinctly identifiable but the ability to differentiate small-scale roughness from noise has yet to be demonstrated. Figure 12 shows the 10 cm roughness profile along a joint surface at the Bankal tunnel.
4.4.4 Analysis of structurally controlled overbreak

A further application of the discontinuity geometry and position is structural overbreak/wedge failure analysis. Joints sets as well as discrete features can be identified as in 4.3.1 and analyzed for structural instability. Figure 12a shows the post-failure structural characterization of a simple wedge in the crown of 4.5 m diameter railway tunnel (Akershus site). Figure 12a also illustrates the repetition of two of the three joint sets elsewhere in the crown.

Figure 12b illustrates the potential wedge failure geometries identified in Unwedge (Rocscience 2007) based on the structural analysis method illustrated in Figures 9 & 10.

Overbreak of more complex geometry can also be analyzed by fitting multiple planes. An example of a larger scale structural overbreak is shown in meshed rock model(Fig. 13). The height of overbreak above the tunnel design profile is computed and displayed as coloured contours(Fig. 14).
The ability to extract the exact location of discontinuities in 3-dimensional space can also be advantageous for the creation of a very complete database for block modeling. Sources of rockfall hazard have been assessed with lidar data in this way to produce more complex and representative block models than traditionally possible (Lato et al. 2007).

4.4.5 Projection of structural features through multiple scans

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 installment. The alignment of scans from successive blast rounds is advantageous for identifying, characterizing and extrapolating larger scale discrete structural features 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.
The identification and precise location of these features may be of particular interest in tunnelling projects with adjacent, parallel excavations, i.e. twin tunnels or benched excavation. A calcified shear zone is visible in a photograph of the third round (Fig. 15a) and defined geometrically in the rock model through three face scans (Fig. 15b).

Figure 15. a) Photograph of calcified shear zone in round 0+10 m b) Aligned face scans with intersecting planar shear zone, Sandvika site

5 CONCLUSION

The application of lidar technology has been expanding away from its more traditional environments and shows great potential in the tunnelling industry. Many applications exist for the high density, high accuracy 3-dimensional point cloud models created that can benefit contractors and supervising engineers. With the reduced scanning times of new lidar systems, data can be collected without interrupting the excavation workflow. The authors have demonstrated the successful implementation of static lidar scanning at the three sites near Oslo, Norway.

The alignment of successive rounds provides permanent digital documentation of the rock mass and installed support. Further in-lab analysis of the collected data has yielded detailed geostuctural characterization, both at the meso- and macro-scale.

Research is ongoing to improve and verify geotechnical analysis of tunnel scans including volumetric data, semi-automated joint extraction, joint surface characterization, and predictive as well as post-failure geometry.

6 ACKNOWLEDGMENTS

The authors wish to thank the Norwegian Geotechnical Institute for their support and collaboration, in particular Elin Morgan, Arnstein Aarset, Eystein Grimstad and Suzanne Lacasse. Thanks are also due to Jean Hutchinson of Queen’s University. The cooperation of the Sandvika-Asker Tunnel Project (Norwegian Railroad Authorities, JBV) for the field trials is appreciated, in particular Linda Nesje and Odd-André Rustad for their support onsite. Funding was provided by NSERC, NGI – KMB project, PREA and GEOIDE.
REFERENCES


BeverControl. [http://www.bever.no](http://www.bever.no)


Leica Geosystems AG 2008a. HDS6000 Product Specifications. Heerbrugg, Switzerland.


