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Development of an elliptical fitting algorithm to improve change detection capabilities with applications for deformation monitoring in circular tunnels and shafts

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ABSTRACT

Terrestrial laser scanning, also known as Light Detection and Ranging (LiDAR) is an emerging technology that has many proven uses in the geotechnical engineering community including rockmass characterization, discontinuity measurement and landslide monitoring. One of the newer applications of LiDAR scanning is deformation monitoring and change detection. In tunnels, deformation is traditionally measured using a series of five or more control points installed around the diameter of the tunnel with measurements recorded at regular time intervals. LiDAR provides the ability to obtain a more complete characterization of the tunnel surface, allowing for determination of the mechanism and magnitude of tunnel deformation, as the entire surface of the tunnel is being modeled rather than a fixed set of points. This paper discusses terrestrial LiDAR scanning for deformation mapping of a surface and for cross-sectional closure measurements within an active tunnel using an elliptical fit to data for profile analysis. The methods were found to be accurate to within a few millimeters when measuring 58 mm of diametric difference over an 18.3 m diameter circular profile, even when some sections of the data were removed from the analysis.

1. Introduction

Light Detection and Ranging (LiDAR) is a technology used for quickly acquiring three dimensional point cloud data. By emitting a laser and measuring either the time elapsed or the phase shift in the returned beam (depending on the scanner type) the scanner collects both three dimensional (3D) positional data (x, y, z) and a return intensity (i) (Shan and Toth, 2008). The newest scanners can collect over one million points per second.

Multiple LiDAR scans taken at different times and distances from an advancing tunnel face can be compared to determine the deformation profile of a tunnel and how it is changing over time. This information could be applied to back analyses to determine stress orientations and to aid in the design of support systems.

To facilitate the use of LiDAR point cloud data for deformation monitoring, appropriate workflows and data analysis techniques must also be developed. Authors have begun to develop these techniques for use in various geological environments such as tunnels (Van Gosliga et al., 2006), landslides (Jaboyedoff et al., 2009), volcanic environments (Nguyen et al., 2011) and rockfalls (Abellan et al., 2011). To use LiDAR scan data for tunnel profile analysis and back calculation, a new method of data analysis involving elliptical fitting is proposed by the authors. This new method allows for both the best fit ellipses for multiple scans as well as the raw LiDAR profiles to be analyzed to gain the maximum amount of information from the scan data. The methods developed in this study are intended for use with scans of bare rock surfaces, as they are capable of providing a global measurement of deformation in the presence of locally noisy data (i.e. roughness). The methods can also be applied to smooth surfaces, however, such as shotcrete or concrete linings to measure their deformation as well.

2. Deformation monitoring in tunnels

During the excavation of a tunnel or other underground space, the in situ stresses are redistributed around the excavated area. The redistribution of the stress field results in a tendency for closure of the void created by the excavation (Terzaghi, 1942). This closure or deformation is generally referred to as convergence when it occurs in a tunneling environment. The magnitude of deformation is related to the rockmass conditions, the magnitude, orientation and ratio of the in situ stresses, the excavation method

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and rate, and the type and location of installed support. Monitoring tunnel convergence is an integral part of modern design and construction techniques.

The objectives and requirements of deformation monitoring programs are different for different tunneling environments. In mountain tunneling environments, small deformations of the tunnel walls are generally acceptable (centimeters of tunnel closure over meter scale tunnels). In contrast, when tunneling in shallow urban environments, even small deformations may be unacceptable, as they have the potential to cause settlement of surface structures. As a result, in urban environments, high accuracy, high precision measurements of deformation are necessary.

Monitoring deformations is beneficial when the New Austrian Tunneling Method (NATM) or observational method for tunnel excavation is being used (Wittke et al., 2006). Deformations can serve as an early warning for more severe failures. Results obtained from monitoring programs can also be used to back calculate rockmass parameters for use in future modeling activities and for refinement of support design.

2.1. Traditional monitoring techniques

There are many existing technologies for measuring tunnel wall convergence. These include, but are not limited to: tape extensometers, total station surveying (or other geodetic methods), photogrammetric devices, and laser profilers. Historically, deformation in tunnels has been measured using extensometers or INVAR tapes, which provide the relative displacement between two points. With the use of theodolites and total stations, absolute distances can be measured and deformations can therefore be linked to external coordinate systems. Today convergence control points are generally established and measured soon after excavation and the installation of support. Measurements are then repeated daily until movements stabilize. Measurements of deformation are generally made during construction, and are sometimes continued well after construction is completed if deformations have not stabilized and continue to pose problems during operation (Kontagianni and Stiros, 2005).

Tape extensometers are the most accurate of all the commonly used deformation monitoring technologies (Fig. 1a and b). They have an accuracy of ±0.2 mm over 10–15 m (Kavvadas, 2005). Barla et al. (2008) has demonstrated the use of this technique and the value of recording convergence by the measurement of five control points around a tunnel cross section. The main limitation of tape extensometers is that they only have the ability to measure movement along a specific line; this also implicitly means that they cannot detect rigid body translation or rotation of the rockmass. They also must be permanently installed in the walls of the tunnel, which interrupts the construction process of the tunnel.

Total station surveying makes use of optical reflectors installed around the tunnel profile (usually five to seven points) as well as a stable reference point outside the zone of convergence to measure deformations (Fig. 1c and d). The station must be moved progressively forward from the location of the stable reference points to the tunnel face, as it progresses. Total stations have an accuracy of about ±2.5 mm over 100 m for tunneling applications (Kavvadas, 2005).

Photogrammetric devices require that a number of reference points be installed on the surface of the tunnel. Photogrammetric devices, where the camera's position is located using a total station, have an accuracy of about ±4 mm (in addition to the total station error) in tunneling applications (Kim et al., 2008).

Some innovative methods for remotely measuring deformation in tunnels include the use of broken ray videometrics, where a series of relay stations are compared to a reference target (Qifeng et al., 2008), and the use of charge coupled device (CCD) cameras with targets (Nakai et al., 2005). The "tunnel convergence monitoring system" developed by Hashimoto et al. (2006) involves the use of connecting rods, displacement gauges and inclinometers installed at certain cross-sectional locations. The device places universal displacement gauges in an octagonal shape around the tunnel profile. The length of the rods and the angle between them is measured, with seven points to one reference. This method is very accurate, but requires permanent installation of the measurement devices.

2.2. Georeferencing and absolute positioning

For the purposes of performance monitoring or back analysis of single or non-interacting excavations, either relative or absolute measurements of tunnel convergence and deformation can be made. Before the advent of georeferencing, relative measurements were the only option for measuring tunnel convergence. Today, as total stations and global positioning systems (GPS) are very common, absolute positioning has become the state of practice for convergence measurements. In tunnels, total stations and survey markers are generally used for absolute positioning. The main advantage that absolute positioning provides in tunnel deformation monitoring is that it adds the ability to measure vertical and lateral shift in the tunnel, as well as allowing referencing to an external coordinate system (Kontagianni and Stiros, 2003).

Absolute positioning is not necessary to characterize deformation in a single bore tunnel, where diametric convergence is being measured. Absolute positioning is necessary in twin bore tunnels, however, when the vertical and lateral shift in one tunnel can affect the stability of the other tunnel. Absolute positioning and displacement measurement may also be required where surface or infrastructure settlement is being monitored.

When using relative positioning to characterize tunnel convergence it is important to consider the diametric convergence instead of the radial convergence, to ensure any errors due to the misalignment of the centroid of the tunnel are eliminated (Fig. 2).

2.3. Position referencing in an active tunneling environment

To implement any type of deformation monitoring near the face of an excavation where a tunnel boring machine (TBM) is being used, absolute positioning is likely not possible. Data will need to be collected rapidly and possibly with little warning or time for preparation, when a break in the TBM operations permit access for scanning the tunnel. The locations for measurement must also be flexible; certain areas of the tunnel wall will inevitably be missing from the scan data (occluded) due to objects in the scanner's line of sight, as parts of the tunnel wall will be blocked by machinery, ventilation, conveyor systems or the TBM itself.

In an active tunneling environment, it is not always practical or possible to maintain permanent survey markers. For total station measurements of convergence, prisms are usually installed at certain sections around the perimeter of the tunnel. If one of these prisms is knocked out of place or comes loose, convergence measurements can no longer be made from that point. Also, if one of the prisms were installed in an area of anomalous movement, the data collected would be useful for characterizing that section of deformation, but would not provide information that could be used for back analysis of overall trends.

2.4. Back analysis using deformation measurements

One of the main reasons deformation measurements are collected is for back analysis. Back analysis is useful for monitoring the stability of excavations, for calculation and interpretation of field stresses, and for calculation of rockmass parameters such as deformability. Many authors have explored different methods for