The Development of a Distributed Optical Sensing Technique to Monitor Forepole temporary support elements employed within an Umbrella Arch System

Vlachopoulos, N., Forbes, B., & Oke, J.
GeoEngineering Centre, Queen's-RMC, Kingston, Ontario, Canada

Hyett, A.J.
YieldPoint Inc., Kingston, Ontario, Canada

ABSTRACT: Temporary support for a tunnel excavated in weak rock can involve (but is not limited to) the utilization of a combination of steel-sets, rock bolts, shotcrete, spiles/forepoles and/or face stabilization technologies. The purpose of such tunnel support is to maintain confinement for the rock mass in order to help the rock mass support itself. This research is concerned with the forepoles as components of this system. Within this context, this paper describes a novel application of a distributed optical sensing technique specifically for monitor the continuous strain profile along forepole elements. The procedure employs a distributed optical sensing technique using optical fiber that is based on Rayleigh backscattering which has been previously been employed with grouted rock bolts. The paper outlines the technology, describes how it has been adapted for monitoring of forepoles, and assesses its potential and limitations based on initial laboratory experiments.

1 INTRODUCTION

Classical tunnel designs have been based on the Rock Mass Ratio (RMR) (designing with respect to deformations) and Terzaghi based designs (designing primarily to support all loads including overburden pressure by the final lining). A newer tunneling method, such as the New Austrian Tunneling Method (NATM), incorporates an observational approach that is deformation based. This method integrates the surrounding rock into the overall support structure (i.e. the supporting formations will themselves be a part of the supporting structure as the rock is able to support itself to a certain degree) (Romeo, 2002). Using the NATM, a controlled deformation of the rock mass is permitted (a limited strain of approximately 1%) and this gives the stresses an opportunity to be partly released and less stiff and thus a less-expensive support system can be used (Kondogianni and Stiros, 2002).

Optimizations of tunnel support design (to include individual support elements, forepoles, shotcrete, rockbolts etc.) can therefore be achieved within the framework of this observational (well instrumented) approach whereby the behaviour of rock/soil, support elements, geomaterial-support interactions, and behaviours can be explicitly determined. Through back-calculations, material properties can be clearly derived. However, there exists a gap in knowledge in terms of the distinct performance of each support element in isolation and its performance as part of a multi component support system. This investigation, then, suggests a strategy in order to determine the continuous behaviour and performance of a forepole temporary support elements as part of the overall temporary support scheme.

2 BACKGROUND

2.1 Umbrella Arch and Forepoles

The Umbrella Arch (UA) (Figure 1) is a tunnel pre-support system that reinforces through the interaction of support and rock mass, installed during excavation above and around the crown of the tunnel face. The Umbrella Arch can consist of a variety of support elements, however, for the purposes of this paper, a UA system with forepole elements was investigated. Forepole temporary support elements are installed when a difficult and/or weak material is consistent for a large portion of the tunnel alignment and where there is a large potential for multiple geological structures of unfavorable orientation/structures to contribute to a possible failure. The UA reduces/controls surface settlement for shallow tunnels and minimizes displacements. By definition, a Forepole is a support element of an Umbrella Arch that is composed of metallic longitudinal members that are greater than the height of the tunnel (Oke et al., 2013). Forepoles are used ahead of the face (in combination with other temporary support), adding stabilization ahead of the plastic zone created due to the tunneling effect. They are installed longitudinally in order to allow for stable excavation underneath the structural umbrella (UA).
formed by an arrangement of multiple forepoles (Figure 1).

In terms of their physical, design parameters, forepoles are long, steel cylindrical pipes commonly 12-15m long. Their internal diameter is typically between 60 mm and 200 mm with a wall thickness of 4 mm to 8 mm. However, thicknesses (t) up to 25 mm have also been used. Selected parameters of interest are also located within Figure 1. Generally, forepoles are inserted at a slight angle (3°-7°) above the top of the tunnel profile, while maintaining the same tunnel opening dimensions. In terms of their mechanistic behaviour, forepoles support in the radial direction, however, they also react in the longitudinal direction. This bi-directional nature of the forepole support and reaction further emphasizes the need to analyze these systems in three dimensions and to determine the complete and continuous performance of such elements in-situ with a view of optimizing their design.

2.2 Optical Sensing Techniques

Electrical and mechanical transducers have been the standard practice for structural support monitoring. This convention is now being challenged by the use of fiber optic strain sensing technologies. Optical sensing provides the unique opportunity of using a single transducer or single optical fiber for monitoring an array of measurement points. In comparison, conventional monitoring technologies such as the resistive foil strain gauge require a transducer for every measurement point. In many cases this will limit the extent of conventional monitoring due to the increased cost and manufacturing difficulties adding more measuring points introduces.

Several methods of optical strain sensing are currently available that use standard single-mode-fiber (SMF); a low-cost telecom fiber. These include technologies that are Raman, Brillouin, and Rayleigh scattering based, as well as Fiber Bragg Gratings (FBGs) based techniques.

2.3 Fiber Bragg Gratings (FBGs)

The FBG technique measures strain from a wavelength-dependent reflection spectrum caused by periodic modulation of the refractive index in the core of a single mode fiber. Referring to Figure 2, the reflected Bragg wavelength, $\lambda_B$, will change as the fiber is strained. This results from an alteration in the period of index modulation, $\Lambda$, as the fiber undergoes compression or tension.

$$\varepsilon = \frac{\Delta \lambda_B}{\lambda_B} \times \frac{1}{1 - \frac{n^2}{2} \left[ p_{12} - v(p_{11} + p_{12}) \right]}$$ (1.0)

Figure 1: a) Nominal temporary structural support system used as part of the observational method of support. Elements shown are: forepoles without niches; steel sets (i.e. H-piles); shotcrete; and rockbolts. Lf: length of forepole; Lfo: length of forepole overlap b) Cross-sectional plane view of steel set, forepole layout and geometry. Parameters of interest are: Dc: tunnel diameter, Sbf: spacing between forepoles, Scf: spacing center to center of forepoles; Df: diameter of forepole pipe, tf: thickness of forepole pipe. c) Forepole installed at the crown of a tunnel excavation at the face. d) Forepole installed in a configuration whereby they are resting on steel sets immediately in front of the excavated tunnel face.

Figure 2: Illustration of a uniform Bragg grating structure in a single mode fiber (left). Also shown is an example of the reflected Bragg wavelength (right). Modified after Venghaus (2006)
In comparison to conventional strain techniques, FBGs have the capability of monitoring accurately over longer distances. Yet, similarly, additional Bragg grating structures must be inscribed into the fiber to increase the number of discrete measurement points. As such, increasing spatial resolution becomes increasingly costly and difficult to manufacture.

2.4 Distributed Optical Sensing (DOS)

As light travels through a transparent medium, a SMF, a small portion will scatter back over the entire length of the medium, termed backscatter. This phenomenon was identified by Rich & Pinnow (1972) as displayed in Figure 3. The distributed optical sensing technique monitors backscatter. Similar to Bragg wavelength, backscatter is dependent to strain. Several methods based upon Raman, Brillouin, and Rayleigh analyze backscatter over the entire length of fiber under consideration; which in turn can provide a continuous strain profile of the fiber.

Raman based methods monitor the intensity of specific components in the back-scattered spectrum while Brillouin and Rayleigh methods are frequency based. A fascinating aspect of techniques based on Raman and Brillouin is the capability of monitoring strain over very long ranges, upwards of 50 to 100kms. However, these methods are limited to spatial resolutions in the order of 0.1 to 1m. Techniques based on Rayleigh backscatter are capable of incredibly high spatial resolutions, 1.25 to 5mm, but the maximum monitoring length is reduced to a range of 20m.

3 APPLICATION OF DOS IN GEOTECHNICAL ENGINEERING

There often exists a level of uncertainty of the in-situ stress, rock mass conditions, etc. in Geotechnical engineering. As a result, the advancement of numerical models is hindered by a general lack of confidence with input parameters. This paper proposes a method for optimizing the solutions of numerical models by applying DOS as a validation/verification tool in a cyclical approach, Figure 4.

![Figure 4](image)

Figure 4: An optimization cycle which should continuously be circled to validate and progress the state of support elements. Modified after Diederichs & Hutchinson (1996)

3.1 Application with Temporary Support Elements

A novel concept is coupling or embedding DOS technology with temporary support elements used for controlling excavation stability. In many cases the state of the support elements can detail surrounding ground conditions, as discussed by Mohamad et al. (2007a). Brillouin based DOS was installed around the circumference of steel support rings in a twin tunnel excavation. The circumferential strains were monitored and also compared to surface settlement surveying. Analysis of the results were able to reveal a faster development of strains in the steel support rings than surface settlements during excavation.

This same Brillouin based DOS was applied to secant piled wall along with chain inclinometers, Mohamad et al. (2007b). A comparison of observations from each technique is shown in Figure 5. The measured values of displacement and curvature for each technique are very comparable however, DOS has the advantage giving a direct strain output. Conversely, strain must be differentiated from chain inclinometer measurements. DOS also allows axial behavior of the wall to be monitored.

This work is particularly of value with respect research involving forepoles. Volkmann & Schubert (2008) have conducted multiple in-situ experiments using chained-inclinometers and geodetic surveying in order to measure the effects of forepoles ahead of the tunnel face, on tunnel convergence, and on surface settlement. The advantages of DOS present by Mohamad et al. warrants application of this technology to forepole elements in pursuit of verification and development of existing knowledge.

![Figure 5](image)
3.2 Verification of Rayleigh DOS with Rebar

Hyett et al. (2013) demonstrated the potential for the use of Rayleigh based DOS with support elements. Optical instrumentation was embedded along diametrically opposed grooves machined into steel rebar. The fiber was looped at one end of the rebar such that both sides of the support element were monitored using one instrument. The very sensitive spatial resolution of Rayleigh based DOS allows for a continuous strain profile to be monitored along the entire length of a single optical sensor. The case of simply supported rebar under symmetric loading is shown in Figure 6.

The elastic response could have also been monitored using conventional, discrete strain techniques. However, a limited spatial resolution can often result in a misinterpretation and/or omission of specific aspects of load distribution. For example, the strain profile of a grouted section of rebar (i.e. rockbolt) subjected to an axial pull test. Results obtained using Rayleigh DOS are displayed in comparison to foil-resistive strain gauges in Figure 8 and Figure 7 respectively.

Both measurement techniques show strain to decay as an exponential function, discussed by Serbousek and Signer (1987). Results from DOS also detail periodic disturbances corresponding to spacing of rebar ribs. This effect, as modelled by Jalalifar (2006), would require specific placement of discrete instrumentation to be monitored. The continuous strain profile obtained using DOS makes this trivial, as locations of significant loadings do not need to be known priori. This is very advantageous for monitoring temporary support elements, such as forepoles, which often will be subjected to complex loading and discontinuum rock mass behaviour.
Forepole support will regularly comprise bending, axial, and shear loading. Monitoring of the latter has been limited by previous strain technologies. Using DOS shear behaviour was evaluated of a rebar element grouted into three concrete blocks (40MPa mix) with preformed and reamed boreholes, Figure 9. Similar to simulations performed by Jalalifar (2006), a distinctive shear couplet is monitored across the perpendicular shear planes. This validates the potential for DOS to locate unknown discontinuities in-situ.

Rayleigh based DOS is the ideal instrumentation choice to monitor the mechanistic behaviour of forepoles. The highly sensitive spatial resolution allows a continuous strain profile to be monitored and furthermore eliminates the need to know significant loading location priori. Of significance is the fact that continuous strain profile monitoring of a 10-15m long forepole in-situ can be used to predict ground conditions (i.e. discontinuities and/or areas or weakness etc.) ahead of the tunnel face.

4 INITIAL FOREPOLE EXPERIMENTATION

This paper focusses on the proof of concept and summarizes the initial results of utilizing DOS elements for the purpose of determining the true continuous strain behavior of the forepole by creating a feedback-loop between temporary support design and observation. Initial laboratory tests have been conducted to validate Rayleigh based DOS as appropriate monitoring tool for future laboratory and in-situ experiments. The tests were conducted using a 1.5m long, ASTM-A36 four-inch-schedule-40 pipe (NPS: OD=114.30mm, wall thickness=6.020mm). Optical instrumentation was embedded along the length of a 1.55mm deep, machined groove using an epoxy resin.

4.1 Three-Point Flexural Tests

The setup shown in Figure 10 was used to monitor the flexural response of the forepole element. Instrumentation was orientated to observe the top, compressed, section of the forepole under incremental loading from 0 to 25kN; well within the elastic range of the steel element. These loading conditions caused plastic deformation of the epoxy resin which encapsulated the optical instrumentation, specifically at the point of loading. The residual strain profile clearly shows the section of epoxy that responded elastically; returning to a zero strain value. It should be noted that a platen piece was used in order to ensure load was applied directly to the steel element and not the instrumentation.

The experimental results for elastic sections compared within ±5% of calculated Euler-Bernoulli beam values: as concluded by Hyett et al (2013), shown in Figure 10. The transition from elastic to plastic deformation is clearly distinguishable and was repeatable in subsequent tests without the platen piece.

4.2 Four-Point Flexural Tests

The same loading conditions were used to conduct a four-point flexural test, shown in Figure 11. Experimental results deviated no more than ±7.5% of Euler-Bernoulli beam theory and constant moment was observed between the two locations of applied force. The epoxy resin used for initial experimentation was not ideal for monitoring elastic loads; however, it offered insight into the potential for the technology to be used to monitor plastic deformation/failure of forepole support elements.

5 CONCLUSION

This line of research has demonstrated its innovation in terms of continuous strain profiling of a forepole element in a laboratory environment. Rayleigh based DOS has been discussed as novel opportunity to improve upon the current understanding of the forepole temporary support element. State of the art spatial resolution, 1.25mm, allows a continuous strain profile to be monitored. Such continuous strain profiling of a forepole is particularly important when trying to determine the mechanistic behaviour of such support elements within the overall umbrella arch system. Moreover, the observational method of tunnel design and construction is based on data obtained and interpreted from monitoring instrumentation. Such a technique would certainly have its merits in the field in order to assess the support capacity and performance. Further, there is the potential in the field that continuous monitoring along the length of a forepole can be used to predict ground conditions (i.e. discontinuities and/or areas or weakness etc.) ahead
of the tunnel face. Future laboratory testing (ongoing) will include forepole specimens embedded in ground conditions mimicking construction sequences, true installation geometries and orientations and temporary support arrangements at realistic working stresses.

6 REFERENCES


