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Improving Ground Support Design with Distributed Strain Monitoring

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ABSTRACT

An experimental application of a distributed optical strain sensing technique is presented with forepole support members of the umbrella arch tunnel support system. A laboratory testing scheme was conducted to verify the capability of the optical technique to capture expected support behaviour throughout all stages of construction as well as to demonstrate the potential to be used a novel geotechnical tool for optimizing support design in response to future ground conditions.

RÉSUMÉ

Une application expérimentale d'une technique de détection optique des déformations distribuées est présentée avec les pieux d'étalement du système de soutien de tunnel en arche de type parapluie. Un programme d'essai en laboratoire a été mené afin de vérifier la capacité de la technique optique à capturer le comportement du soutien attendu à toutes les étapes de la construction, ainsi que pour démontrer le potentiel d'utilisation en tant qu'outil géotechnique servant à optimiser la conception de soutien en réponse aux futures conditions du sol.

1 INTRODUCTION

The design and application of ground support has become increasingly critical as the demand for subterranean transportation and resource management has led to many tunnels being developed through urban settings. In such situations, the ground support design will be contingent upon the anticipated ground conditions as well as the project specific requirements and limitations. These will often include the control and mitigation of surface settlements in order to minimize the interaction of the tunnel construction with existing infrastructure (e.g. buildings, highways, rail tracks). A correct and accurate evaluation of the support system performance will therefore be critical to both the safety and economics of the construction process. This necessitates a monitoring

program capable of capturing support system behaviour as to verify or falsify the assumptions made during the design stage (Schubert 2008) and as the excavation advances. An observational tunneling approach, as provided by the Austrian Society for Geomechanics (2010), assesses excavation driven displacements in such a manner; however, the current monitoring practice is often limited to capturing the inner profile of the excavation and conditions at surface (i.e. geodetic monitoring). This is particularly problematic in terms of support design as many support systems installed for settlement management will generally be composed of members that extend ahead of the excavation face, for example the umbrella arch temporary support system (refer to Figure 1 and Figure 2). In this regard, the behaviour and performance of the ground and ground-

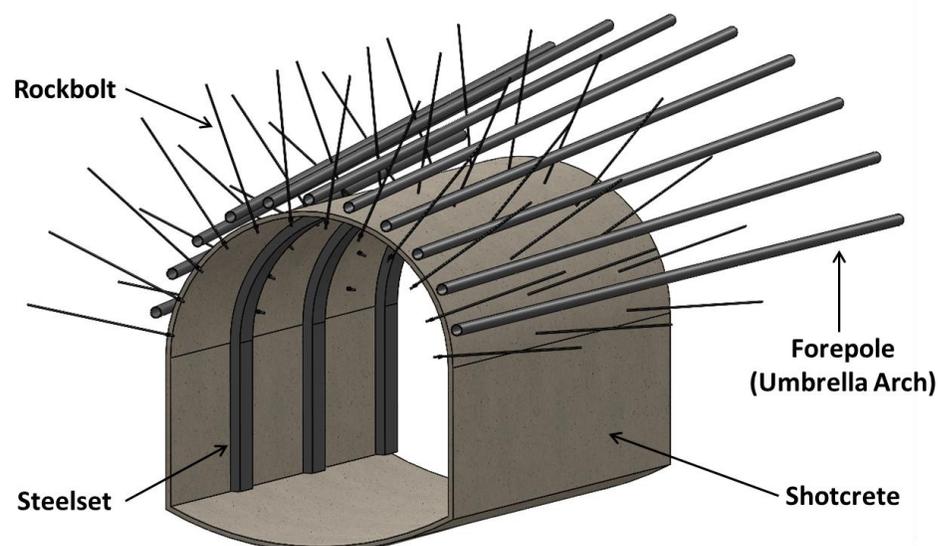


Figure 1. Example tunnel temporary support scheme including: rockbolts, steelsets, shotcrete, and forepoles (composing an umbrella arch).

support interaction in the region ahead of the excavation may be misrepresented or even excluded.

In order to address this limitation of the current monitoring practice, Forbes et al. (2014) proposed equipping forepole support members of the umbrella arch temporary support system with a distributed optical strain sensing technique. The results from laboratory tests demonstrated the optical technique to be capable of capturing a continuous strain profile (i.e. a sub-centimeter spatial resolution) along the length of an instrumented support specimen; however, the technique required further development to be adequately suited for expected loading mechanisms and conditions of forepole support members *in situ*. Within this context there remains an opportunity to optimize support design, and in turn, tunnel performance within the framework of a state-of-the-art observational (i.e. well instrumented) approach whereby the behaviour of ground/soil, support elements, and ground-support interaction can be explicitly determined and further derived for input into empirical and numerical simulation.

2 THE UMBRELLA ARCH

The umbrella arch is a temporary support system forming a structural umbrella from the insertion of an assortment of longitudinal support members installed from within the tunnel, above and around the crown of the tunnel face. The umbrella arch is often considered a pre-support technique as the support members are installed prior to the first pass of excavation. In this manner, the umbrella arch provides support to the ground ahead of and at the

working face as well as the unsupported span immediately behind the working face, inside the tunnel (refer to Figure 2). The latter is a primary distinguishing feature and benefit of the umbrella arch in comparison to other pre-support techniques, such as fiber-glass dowels (i.e. face bolting), which may be used in combination with the umbrella arch.

According to the nomenclature developed by Oke et al. (2014), the longitudinal support members, extending ahead of the excavation face and composing the umbrella arch, can be broken down into three main support elements categories:

- Forepoles: element length greater than the height of the excavation, installed at shallow angles to the tunnel axis (e.g. 15m long steel pipe installed at 5 degrees);
- Spiles: element length smaller than the height of the excavation, primarily installed to control structural driven failure (e.g. rebar); and,
- Grouting elements

This research focuses specifically on the forepole umbrella arch system (refer to Figure 2).

2.1 Forepole Support

Forepoles are passive support elements activated by movements of the ground mass. Their primary support contribution involves the longitudinal transfer of load away from the unsupported span. This is accomplished through bending of the forepole element (often steel pipe), which will be founded on the stiff steelset / concrete lining at two ends (refer to Figure 2 a.) or the steelset / concrete lining

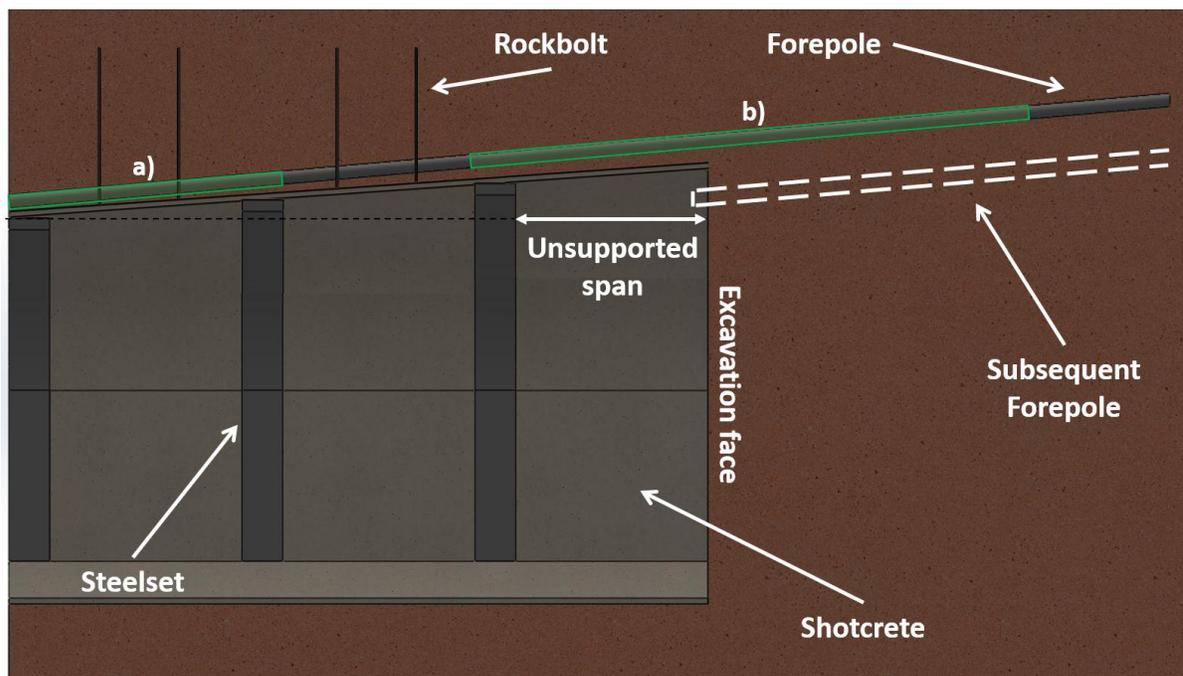


Figure 2. Cross section view of an example forepole umbrella arch support system. Sections a) and b) indicate two loading scenarios of the forepole support element depending on the phase of construction.

and ground ahead of the excavation face (refer to Figure 2 b.) depending on the construction stage. In this regard, the forepole acts as a multi-span beam to provide confinement to the unsupported span during construction (John & Mattle 2002). However, when initially installed the forepole will be subjected to load in a cantilever fashion, as a 1-3m “free length” will exist until the steelset / concrete lining is able to be installed. Furthermore, depending on forepole / grout / ground interaction, axial loading of the forepole may be expected as a result of the stiff element resisting ground movements ahead of the excavation towards the tunnel. Respectively, the ground properties and strength and stiffness of the concrete lining / steelset will play a major role in the support contribution of the forepole elements (Volkman & Schubert 2007).

3 SUPPORT MONITORING

The behaviour of the forepole support individually and as part of the umbrella arch during and transition from the loading conditions, as dictated from the construction sequence, is of design significance. However, a majority of the support behaviour occurs along the embedded length (i.e. ahead of the excavation face) which is inevitably difficult to monitor. Volkman (2004) addressed this issue by installing a series of chain inclinometers (i.e. ten 2m links) in a separate pipe above and parallel to a forepole umbrella arch, extending up to 20m ahead of the excavation face. This work allowed the longitudinal distribution of settlements along the umbrella arch to be captured and behaviour of forepoles to be inferred. Yet, the spatial resolution of the monitoring program was a limiting factor in terms of understanding the mechanistic behaviour of the forepoles throughout the construction process. This limitation is demonstrated in Figure 3 and Figure 4.

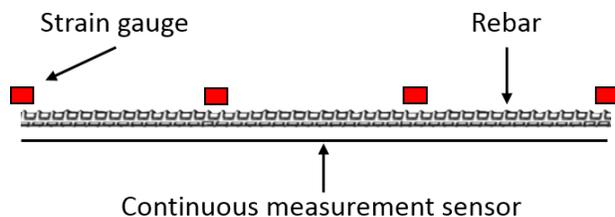


Figure 3. Schematic of a rebar element with four equally spaced strain gauges (i.e. discrete solution) as well as a continuous measurement sensor (e.g. Forbes et al. 2014)

Referring to Figure 3, it is apparent that a large portion of the support member is left unmeasured when comparing the discrete measurement points (i.e. the strain gauges) and the continuous measurement sensor (e.g. the aforementioned optical technique). In this regard, an interpolation of discrete measurement points is required in order to obtain a full profile along the length of a support member. This may be an appropriate approximation under continuous support behaviour; however, consider the discontinuous loading displayed in Figure 4.

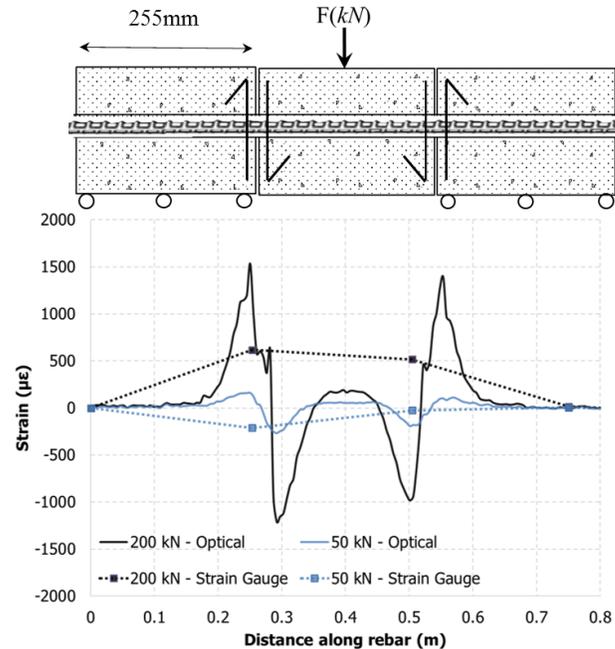


Figure 4. Strain profiles along an instrumented rebar specimen grouted into three individual concrete blocks and subjected to a double shear loading condition (i.e. simulation of shearing bedding layers). Strain profiles are that captured using the optical technique at 1.25mm spatial resolution (i.e. a continuous strain profile) and interpolated between measurement points taken every 25cm.

The strain profiles displayed in Figure 4 expose an inherent dilemma of conventional, discrete monitoring methods. A poor spatial resolution may result in the misinterpretation and possible omission of support behaviour (and in turn the ground behaviour). But to increase the spatial resolution requires additional measurement devices (e.g. more strain gauges), which becomes both increasingly costly and difficult to manage (e.g. protection of additional transducers and lead wires). As a result, a choice will have to be made between having many poorly instrumented zones (i.e. monitoring the entire tunnel) or few highly instrumented zones (i.e. accurately capture the support and ground behaviour locally). In terms of monitoring the forepole umbrella arch, a ubiquitous monitoring solution would be capable of capturing complex discontinuous support behaviour (i.e. determine the mechanistic behaviour of individual elements) while remaining cost effective as to monitor subsequent layers of forepoles installed (i.e. capture the combined support effect of the umbrella arch).

3.1 Distributed Strain Monitoring

The distributed optical strain sensing (DOS) technique discussed in Forbes et al. (2014) provides a unique solution for monitoring forepoles and support in general. The considered technique is capable of monitoring strain with a spatial resolution of 1.25mm along the length of a

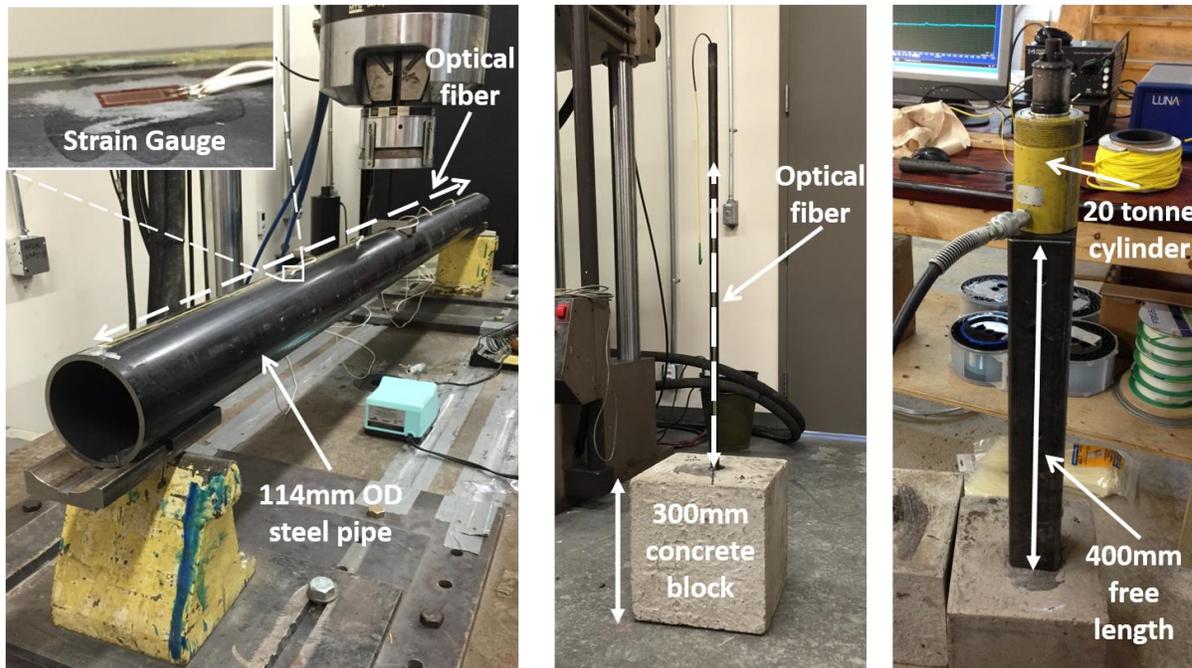


Figure 5. Left: Symmetric bending test apparatus displaying an optically and strain gauge instrumented 114mm OD, 6.02mm thick steel pipe; Middle: Optically instrumented 21.3mm OD, 2.80mm thick, steel pipe grouted into a concrete block for use in axial and cantilever load test; Right: Axial load apparatus. Load was applied using a 20 tonne cylinder approximately 400mm along the optical instrumented steel pipe from the concrete block.

standard, low cost optical fiber. In this regard, thousands of individual, discrete transducers can therefore be replaced by a single (μm outer diameter) optical fiber acting as both the lead and transducer. The development of the optical technique for use with forepole support is discussed herein.

4 PHYSICAL TESTING OF FOREPOLE SUPPORT ELEMENTS

A laboratory testing scheme was conducted using two sizes of ASTM A53 Gr. B (240 MPa yield strength) steel pipe as the a forepole support element: a) 114mm outer diameter, 6.02mm wall thickness and b) 21.3mm outer diameter, 2.80mm thick. The former is a commonly used forepole size in industry. The latter was chosen for comparison with rebar tests conducted by Hyett et al. 2013. The optical fiber transducer was bonded to steel pipes using a metal bonding adhesive by four methods: a) surface mounting to the exterior pipe surface, b) surface mounting to the interior pipe surface (only applicable for the 114mm outer diameter pipe), c) embedding and encapsulating in 1.5mm groove, machined out along the pipe axis, and d) grouting an optically instrumented insert piece inside the steel pipe (only applicable for the 114mm outer diameter pipe). The optical fiber was also bonded along up to four lengths of the steel pipe (i.e. the same fiber was used to capture the strain profile at various orientations along the pipe axis by looping the fiber at the end of the pipe). The optically instrumented steel pipes were then subjected to the aforementioned loading

conditions at various stages of the construction sequence to assess the merits of the optical technique (see Figure 5).

4.1 Symmetric Bending

For a majority of the construction process the forepole support elements will act as stiff beams transferring the radial load to the steelset / concrete lining within the tunnel and to the ground ahead of the excavation face. This multi-span bending of the forepole was simplified to a symmetric three point bending configuration, also discussed by Volkmann & Schubert (2008). Incremental load in a cyclical fashion was applied to the optically instrumented steel pipes at support spans (i.e. length between roller supports) ranging from 0.50-3.00m. A platen piece was used to ensure that load was only being applied to the steel pipe, and not directly to the optical transducer. A comparison of the captured strain profiles along the 114mm outer diameter pipe at support spans of 0.66m and 2.80m under elastic loads is displayed in Figure 6. These plots show the strain profile along the top (i.e. compressed) section of the steel pipe in comparison to beam theory.

The strain profile captured for the 2.80m support span behaves in an expected linear manner; however, the same pipe specimen at a support span of 0.66m deviates from a linear profile. A distinct concentration of strain (or stress) is observed under the region of applied load. This was a general trend observed for the 114mm steel pipe at support spans less than 1.50m, but that lessened (i.e. became more linear) with increased support span. A normalized plot of the strain profiles captured at various

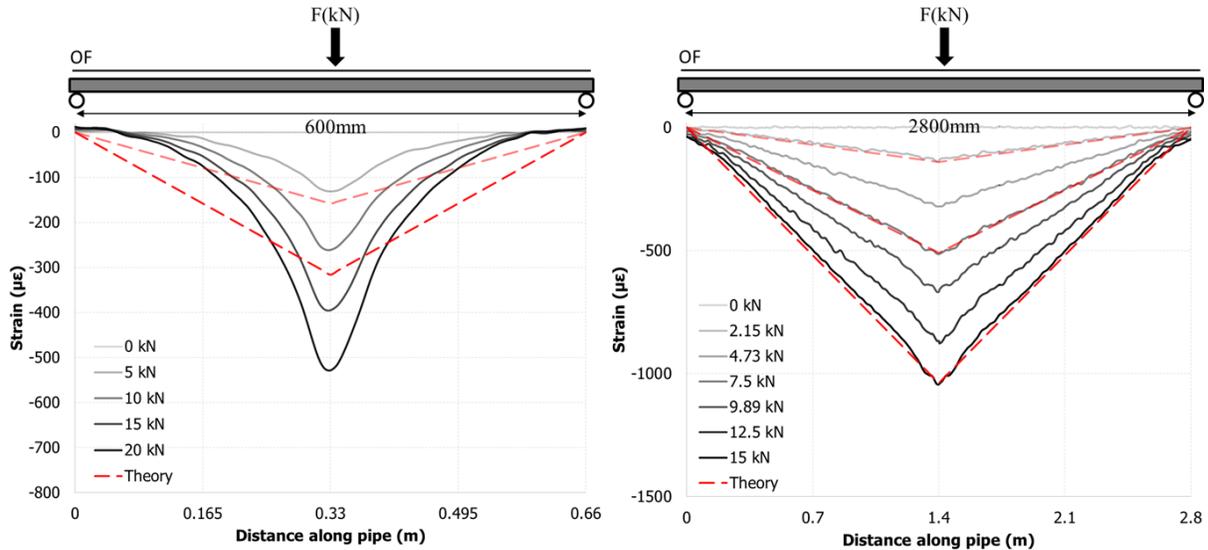


Figure 6. Strain profiles captured in comparison to beam theory along the top (compressed) section of an optical instrumented steel pipe (dimensioned: 114mm outer diameter, 6.02mm wall thickness) at various levels of applied symmetric bending load; Left: 0.66m support span, Right: 2.80m support span.

support spans detailing the transition to expected linear behaviour is displayed in Figure 7.

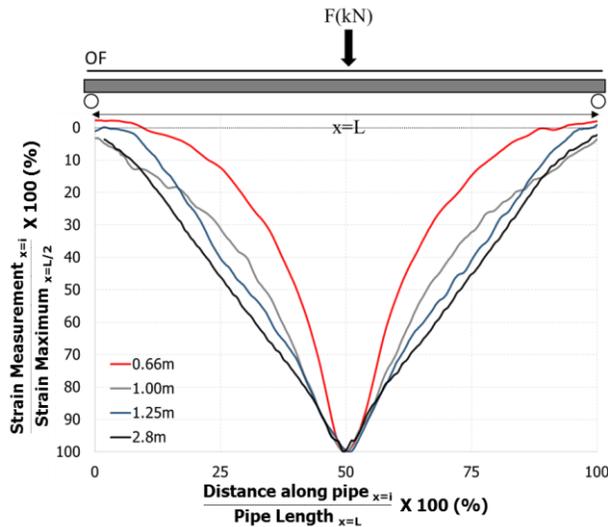


Figure 7. Normalized strain profiles captured along the top (compressed) section of an optical instrumented steel pipe (dimensioned: 114mm outer diameter, 6.02mm wall thickness) at 15kN of applied symmetric bending load for support spans of: 0.66m, 1.00m, 1.25m, and 2.80m.

The results of the elastic bending tests conducted on the 114mm outer diameter pipe bring forth a significant design consideration. In context of material design, the outer diameter and thickness of the steel pipe will govern the stiffness; however, the length the steel pipe under load (i.e. the support span) will also contribute to the stiffness

of the system. In this regard, the supported length in comparison to the second moment area of the steel pipe (i.e. forepole) may detail the pipes natural tendency towards flexural buckling (i.e. elliptical behaviour), which, as seen in Figure 6 for the 0.66m support span, results in higher levels of strain in the pipe than expected. This has potential to lead to an overestimate of the support capacity, leading to unexpected failure of the support system. However, a more accurate simulation of forepole loading would most likely involve a distributed load along the steel pipe. As such, it should be determined if this concentration of strain also occurs under such a loading condition, as it did for the point load, in the elastic range.

The behaviour of the 114mm outer diameter steel pipe was also test post elastic limit. This was performed at a support span of 1.00m using both the optical technique and four strain gauges surface mounted along the steel pipe. The instrumentation was orientated to measure strain along the top section of the steel pipe and is displayed in Figure 8. The results captured using the strain gauges agreed well with the strain at the locations of gauges using the optical technique. Yet, it is debatable whether the strain profile captured with the optical technique could be accurately inferred using only the discrete measurement points; especially at higher loads where strain develops at a much higher gradient.

In addition to the 114mm outer diameter bending tests, a 21.3mm outer diameter pipe with a wall thickness 2.80mm was optically instrumented and subject to a similar symmetric bending load. The smaller steel pipe (i.e. scaled down forepole) behaved in an expected linear manner at all support spans and for this reason was used to conduct the cantilever and axial loading tests. Further details of the symmetric bending on the smaller diameter pipe are discussed by Vlachopoulos et al. (2015).

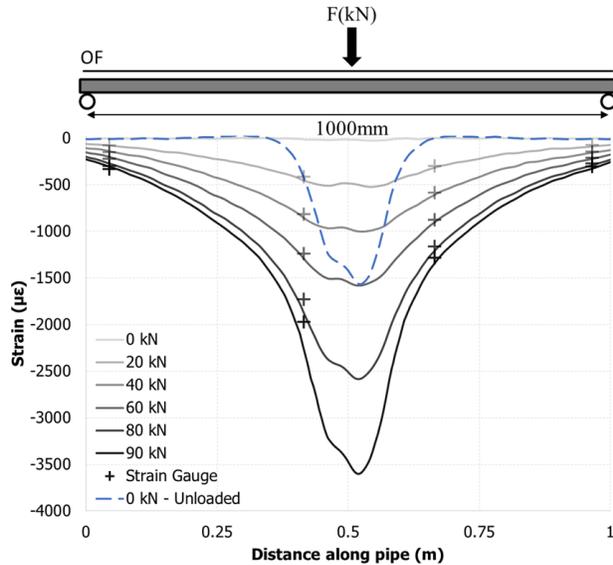


Figure 8: Strain profiles captured along the top (compressed) section of optical instrumented steel pipe (dimensioned: 114mm outer diameter, 6.02mm wall thickness) detailing post elastic behaviour at various levels of applied symmetric bending load in comparison to discrete measurements taken using strain gauges.

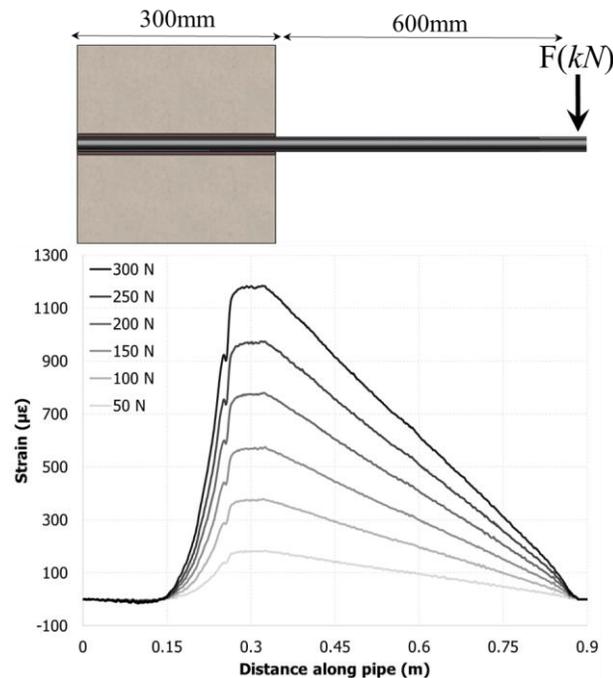


Figure 9. Strain profile captured along the top (tensile) section of a 21.3mm outer diameter, 2.80mm thick steel pipe under a point cantilever load.

4.2 Cantilever loading

The forepole support element will initially undergo cantilever loading during the first 1-3m of excavation after being installed. At this stage of the construction the fore-pole is founded solely in the ground ahead of the excavation face and is relied upon to maintain stability within the region of the working face. This loading condition was simulated by grouting an optically instrumented steel pipe into a 30mm diameter borehole of a concrete block. A point load perpendicular to the axis of the steel pipe was then applied at distances 400-800mm away from the concrete block along the steel pipe, all within the elastic limit of the steel. Referring to Figure 9, a maximum strain is observed at the boundary of the concrete block closest to the applied load, which decays very fast within the grouted section. This behaviour was similarly found with rebar elements by Hyett et al. 2013, which behaves in accordance with beam theory. However, it is important to note that the condition of the ground *in situ* (i.e. damaged excavation face) may result in a strain profile similar to asymmetric bending case (i.e. a less abrupt decay of strain). Furthermore, the elliptical behaviour captured under symmetric bending of the 114mm outer diameter pipe (i.e. concentration of strain at short support spans) needs to be investigated under the cantilever loading condition as it could have profound ramifications on the safety factor of the support design in the unsupported span.

4.3 Axial Loading

The majority of the support contribution of the forepole support elements will be in the form of radial support; however, the forepoles will also be expected to take on a component of axial load as a result of resisting ground movement towards the excavation face. The axial loading was simulated by conducted a pull-out test on an optically instrumented, 21.3mm outer diameter, steel pipe that was grouted into a 30mm diameter borehole in a concrete block. The optical instrumentation was run along diametrically opposing sides by looping the fiber at one end of the steel pipe. The grouted length was 300mm; the entire length of the concrete block. Axial load was applied using a 20 tonne cylinder approximately 400mm from the concrete block along the steel pipe axis (see Figure 5). This implies a 400mm 'free length' of steel pipe between the grouted section (i.e. the concrete block) and the position of applied load which ideally would go into constant tension when loaded. However, this was found to be very difficult to accomplish as any slight imperfection from an ideal axial alignment (e.g. misalignment of the steel pipe within the borehole, initial seating of the cylinder and barrel and wedge used to apply the load to the pipe) will result in a component of bending. This can be observed in Figure 10, displaying the strain profile along opposing sides the steel pipe which essentially mirror each other (one side displays a concave profile which is accompanied by a convex profile on the opposing side). A majority of this bending load can be removed from the results by taking an average of the opposing sides. The average

of the results shown in Figure 10 can be found in Figure 11.

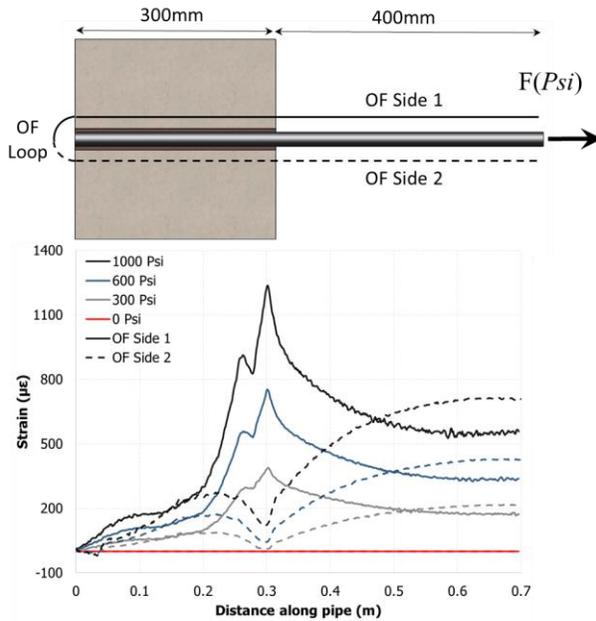


Figure 10. Strain profiles captured along diametrically opposing grooves of an optically instrumented, 21.3mm outer diameter steel pipe, grouted into a concrete block, subjected to axial loading using a 20 tonne cylinder.

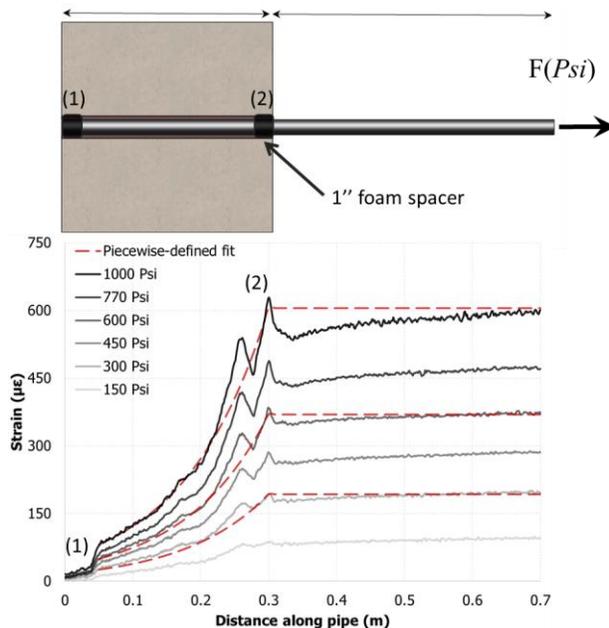


Figure 11. Average strain profiles along an optically instrumented, 21.3mm outer diameter steel pipe, grouted into a concrete block, subjected to axial loading using a 20 tonne cylinder. A piecewise-defined fit was determined for the various levels of applied load.

Referring to Figure 11, the free length of the steel pipe (i.e. from 0.30-0.70m) is observed as a uniform strain level, which is determined by the stiffness of the steel pipe. Along the grouted section of the steel pipe (i.e. from 0.00-0.30m) the strain exponentially decays from the uniform strain level at the loaded end of the concrete block to zero at the unloaded end. A piecewise-defined fit was found from the various levels of applied load in this test and was repeatable in subsequent experiments.

The strain profile was further determined to be influenced by boundary conditions in two manners: a) the grouted length and b) apparatus setup. Concerning the former, minor slip of the steel pipe was captured using an LVDT at the unloaded end of the concrete block; implying an insufficient anchoring length. This gives a possible explanation for the sharp jump and in strain seen from 0.00-0.05m in Figure 11. Concerning the latter, two foam spacers were used to center the steel pipe during the grouting process. The effect of these two spacers is clearly distinguishable in the strain profile, marked as (1) and (2) in Figure 11. Again, it should be noted that features captured in the strain profile, such as the boundary condition effects in Figure 11 and the component of bending in Figure 10, would most likely be misinterpreted or omitted using conventional discrete techniques. As such, the results of the axial tests provide further confirmation of the capabilities of the optical technique to capture complex support behaviour and interaction.

5 CONCLUSION

The distributed optical strain sensing technique has been verified as a novel monitoring and geotechnical tool for capturing the performance of forepole support members throughout all stages of construction. The sensitive spatial resolution allows a continuous strain profile to be measured, overcoming the limitations of conventional, discrete strain measuring techniques, which in most cases will not fully capture the complexities of ground-support interaction. The results of using this instrumentation with temporary support elements in isolation have provided confidence for using such a technique to capture the combined performance of many support elements within an entire temporary support scheme. In addition, the optical technique can be realized as a novel tool with the capability to "see" and "sense" into the ground ahead of the working face, allowing the engineer to react and make adjustments to the support and excavation process in response to future ground conditions. As a monitoring solution, DOS provides unparalleled information concerning the behaviour and the interaction between the ground medium and the support elements which can be back-analyzed for predictive numerical model methods and ultimately support design optimization.

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