International Conference on Case Histories in Geotechnical Engineering

(2008) - Sixth International Conference on Case Histories in Geotechnical Engineering

14 Aug 2008, 11:55 am - 12:15 pm

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Kenichi Soga
University of Cambridge, Cambridge, UK

Hisham Mohamad
University of Cambridge, Cambridge, UK

Peter J. Bennett
University of Cambridge, Cambridge, UK

Recommended Citation

Soga, Kenichi; Mohamad, Hisham; and Bennett, Peter J., "Distributed Fiber Optics Strain Measurements for Monitoring Geotechnical Structures" (2008). *International Conference on Case Histories in Geotechnical Engineering*. 4.
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6th International Conference on
Case Histories in Geotechnical Engineering, Arlington, VA, August 11-16, 2008

DISTRIBUTED FIBER OPTICS STRAIN MEASUREMENTS FOR MONITORING GEOTECHNICAL STRUCTURES

Kenichi Soga
University of Cambridge
Cambridge, CB2 1PZ, U.K.

Hisham Mohamad
University of Cambridge
Cambridge, CB2 1PZ, U.K.

Peter J. Bennett
University of Cambridge
Cambridge, CB2 1PZ, U.K.

ABSTRACT

Recent advances in strain measurement using optical fibers provide new opportunities for monitoring the performance of geotechnical structures during and after construction. Brillouin optical time-domain reflectometry (BOTDR) is an innovative technique that allows measurement of full strain profiles using standard optical fibers. In this paper, two case studies illustrating the application of the distributed optical fiber strain sensors are presented. One is monitoring of an old masonry tunnel when a new tunnel was constructed nearby and the other is monitoring the behavior of secant piled walls for basement construction. Both sites are located in London. The advantages and limitations of this new sensor technology for monitoring geotechnical structures are discussed.

INTRODUCTION

Geotechnhical engineers are sometimes faced with a question “Why they are what they are?” in their professional practice. Professor James Mitchell’s book “Fundamentals of Soil Behavior” originally published in 1976 and the subsequent editions (1993 and 2005) focused on addressing “why” through the development of an understanding of the factors determining and controlling the engineering properties and behavior of soils under different conditions.

“Why” often follows from “What (happened)” through monitoring the behavior of the concern. By understanding “Why”, the knowledge can be applied prudently to predict “What (is going to happen)”. This prediction should be verified again by monitoring. More accurate and more robust data of monitoring and measurements provide a better chance of finding out “why”.

Measurement and monitoring to know “What (is happening)” in geotechnical engineering can be done by taking soil samples and testing them in the laboratory (ideally simulating the field conditions), or by taking measurements in the field during and after the actual construction activities or while natural hazards are occurring. The former is addressed well in “Fundamentals of Soil Behavior”. It is the latter that is the subject of this paper.

Over the last decade there has been a rapid development in the area of smart sensor technologies thanks to innovation in sensor/actuator design and fabrication, fiber optics, micro-electro-mechanical sensors (MEMS) and other electronic devices, signal processing and control, and wireless sensors and sensor networks. It appears that there are great opportunities in geotechnical engineering in adopting these new innovative technologies to know “what (is happening)” to our geotechnical structures.

In geotechnical construction, the concept of ‘observational method’ is often used to monitor the performance of geotechnical structures during construction due to uncertainty in soil-structure interaction. Although monitoring after construction has been limited up to now, the use of innovative sensor technologies allows us to make a new step toward the development of ‘Smart’ Geotechnical Structures.

This paper describes the application of one of these new innovative sensor technologies; that is, the distributed fiber optics strain measurement technique. To follow the main theme of this conference (i.e. learning from case histories), the aim of this paper is to demonstrate the capability of this new technology through actual case studies and discuss the advantages and limitations compared to other conventional monitoring technologies.

STRAIN MEASUREMENTS BY OPTICAL FIBERS

Structural integration of fiber optic sensing systems represents a new branch of engineering which involves the unique marriage of: fiber optics, optoelectronics and composite material science. Optical fiber sensors have a number of advantages over their electrical counterparts. The transmission of light down an optical fiber is an established technique in optical communications for carrying information and is the primary candidate for resident sensing systems. Fiber optic sensing techniques have been developed as part of aerospace research because of its use in monitoring aeronautical and space structures composed of advanced materials. This technology can be transferred to the field of geotechnical engineering to provide new opportunities in sensing.

Design limits can be based on strain developing in the structure. Although strain measurement is well established, current practice has until recently been restricted to measurement of point-wise strains by means of vibrating wire (VWSG) or metal foil strain gauges and more recently by fiber optics utilizing Fiber Bragg Grating (FBG) technology. When instrumenting building components such as columns or beams where the strain distribution is merely a function of the end conditions and applied loading, point sensors are suitable to define the complete strain profile. However, where structures interact with soil (e.g. underground infrastructure such as foundation tunnels or pipelines) or indeed in the case of a soil structure (road or dam embankments), the state of the structure is not fully understood unless the complete in situ strain regime is known. In the context of monitoring strain in piled foundations, tunnels, pipelines, slopes or embankments, capturing the continuous strain profile is often invaluable to pinpoint localized problem areas such as joint rotations, deformations and non-uniformly distributed soil-structure interaction loads.

In this study, we used a unique fiber optics technology called the ‘Brillouin optical time-domain reflectometer (BOTDR)’. The novel aspect of this new technology lies in the fact that tens of kilometers of fiber can be sensed at once for continuous distributed strain measurement, providing relatively cheap but highly effective monitoring systems. The system utilizes standard low cost fiber optics (potentially $0.2/m) and the strain resolution can go down to 2 micro strains.

When a pulse of light that travels down an optical fiber, the majority of light travels through but a small fraction is scattered back at every location of the fiber. As shown in Fig. 1, the frequency of this backscattered light is shifted from the original input frequency by an amount linearly proportional to the temperature and strain applied at the scattering location. By resolving the back-scattered signal in time and frequency, a complete strain profile along the full length of the fiber can be obtained (Horiguchi et al., 1994).

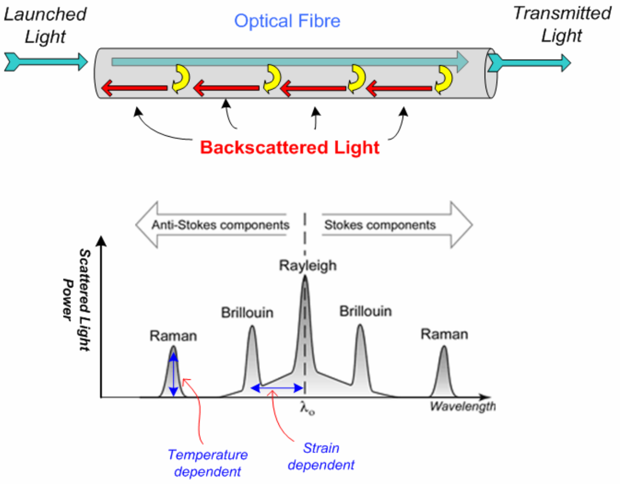


Fig. 1 Backscattered light

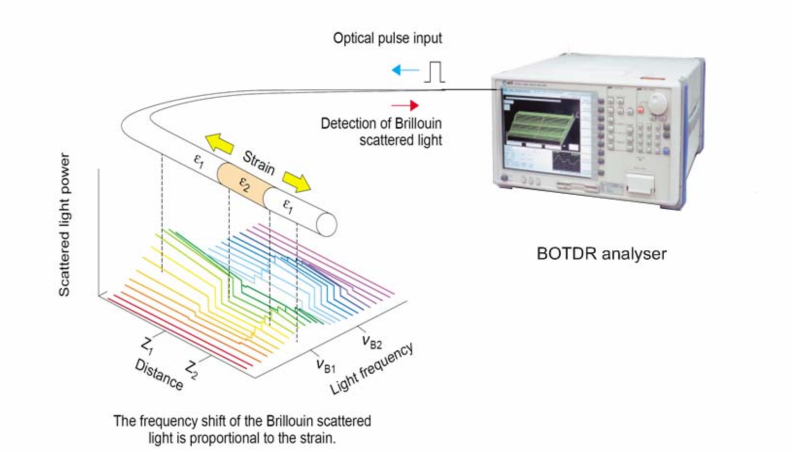


Fig. 2 BOTDR analyzer

A particular advantage of optical fiber technology comes from the low propagation losses that can be obtained with a single mode optical fiber. This means that strain can be measured along the full length (up to 10km) of a suitably installed optical fiber by attaching a BOTDR analyzer to one end (see Fig. 2).

The technique can use standard telecommunication optical fibers providing economic solution; the fiber optic sensors used are the same kind of thin cables used in the telecommunications industry except they are wrapped around or embedded in structures. With this technology, one ordinary optical fiber can replace thousands of point sensors, providing an economic, effective solution.

It is important to note that there are two potential limitations of this technology for civil engineering applications, at least at the present time. (1) The best resolution of currently available analyzers is $10\mu\varepsilon$ (or less for some analyzers), which is more than an order of magnitude greater than the resolution of some point strain measurement devices. Hence, there is a need to demonstrate the importance of distributed measurements with less accuracy than more accurate point measurements. (2) The measurement time for the whole length takes about 5-25 minutes. Therefore, it is not suitable for any dynamic measurements.

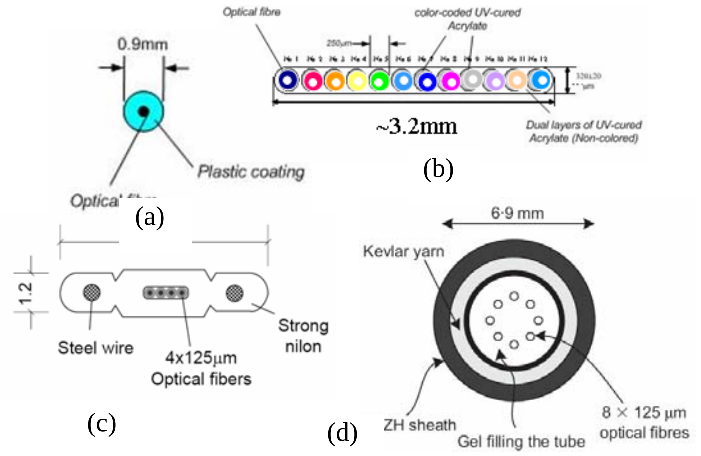
There are several BOTDR analyzers on the market. For further details of these analyzers, see the manufactures’ websites (www.yokogawa.com, www.advantest.com, www.omnisens.ch, www.ozoptics.com, www.sensornet.co.uk).

OPTICAL FIBERS

A simple optical fiber that can be used for BOTDR is shown in Fig. 3a. It has an external diameter of 0.9 mm with a single optical fiber placed in the middle. The plastic coating and the inner glass core are fixed together so that the strain applied externally is transferred from the coating to the inner core. This low cost (~$0.20/meter) is fragile and care must be taken when installing it. A sensing cable with multiple optical fibers such as Fig. 3b is also inexpensive and provides redundancy in case one of the fibers breaks.

Special strain sensing optical fiber cables are also available. Extra layers of protection are often placed around more than one fiber to form a cable. An example of such fibers is shown in Fig. 3c. It is reinforced by steel wires. This is more robust, but still transmits the strain applied through to the glass optical fiber and allows the strain to be measured. Although this is considerably more expensive (up to $20/m), it is likely to be faster to install as they do not require such gentle handling (like for cast-in-place piles).

More robust forms of standard telecom cables have thick plastic coatings, sometimes reinforced with steel, around a gel filled tube containing the optical fibers (as shown in Figure Fig. 3d). This makes these cables unsuitable for strain sensing as the optical fibers move inside the rather than carry strain. But this type of cable can be used to carry the optical signal between the sensing cable and the analyzer. This is particularly useful for connecting a remote monitoring location to the site office as the cable is very robust and still inexpensive (~$1/m).



(a)

(b)

(c)

(d)

Fig. 3 Optical fibers for strain sensing

WHY DISTRIBUTED STRAIN MEASUREMENTS?

Equipment for evaluating the full in situ stress condition of the soil does not exist at the present time; any measurements of soil stresses for understanding soil behavior must be carried out indirectly. For soil-structure interaction problems, the interaction forces (for example, the stresses acting on a pile shaft) are evaluated by accurate evaluation of the strain distribution within the foundation. If a complete distribution of strain along the foundation is given, the skin stress and displacement can be obtained by differentiating and integrating the distributed strain data, which in turn results in transfer load functions.

Accurate local strain measuring technique may supply highly accurate local measurements. However, when the strain distribution for analysis is constructed from them, the advantage of the accuracy is lost. BOTDR, on the other hand, results in a less accurate local evaluation of strain, but this is compensated by a continuous distribution of strain.

The importance of strain distribution rather than accurate discrete measurements can be illustrated using an example of a laterally loaded pile (the case of a 0.5m diameter, 10m long, concrete pile with a subgrade modulus of 20 MPa is considered here). The pile is loaded by a horizontal force of 10t, which leads to a head displacement of 2.4mm. To evaluate any error the accurate solution must be known; we assume that the pile is fixed at its head against rotation, infinitely long, and that the soil behaves as a Winkler type model and is linear elastic. Two measurement systems are considered; (i) BOTDR data with an error of 30με, (ii) Point measurements along the pile (the point measurements themselves are assumed to be infinitely accurate). Any error introduced from point measurements is through interpolation of the spatial distribution of the measuring points.

Fig. 4 shows the comparison of lateral deformation estimates of the pile from the two methods with the assumed accurate solution (the details of the calculation are omitted due to page limitation). Even when the spacing of the conventional point measurement technique is quite small (0.5m), the error is around 20% for the upper section of the pile where the majority of soil pile interaction is taking place. The error in the BOTDR is less then 5%. With regard to the estimation of interaction force, *p*, by differentiating the strain profile, the BOTDR results in less than 5% error for the upper section of the pile. Hence, the error in *p* is not a limiting factor for BOTDR, while it may for conventional strain gauges if they are not spaced closely (i.e. less than 1m apart). If one wishes to establish a p-y curve (the interaction force *p*, due to

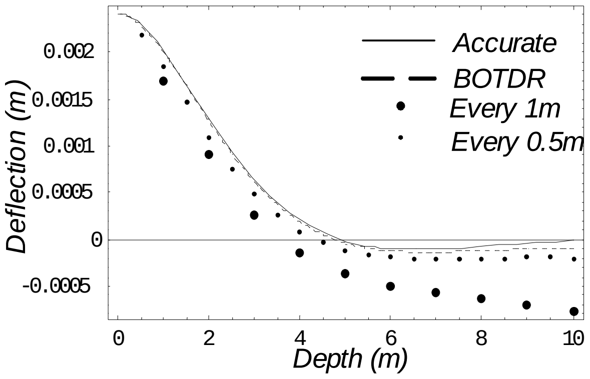


Fig. 4 Comparison of predicted pile deflection

displacement *y*), it is more likely to be successful when BOTDR is used rather than very accurate strain measuring devices which supply only local information.

Further discussion on point measurement against discrete strain measurement is given by Klar et al. (2006).

CASE STUDY 1: MONITORING OF AN OLD TUNNEL

Thameslink Tunnel (8.5 m diameter) is an old masonry tunnel constructed between 1865 and 1868 in London using the cut and cover method. In 2005, new Thameslink 2000 Tunnels (TL2K) were constructed as part of the Channel Tunnel Rail Link (CTRL) and they have an internal diameter of 6m. The northbound tunnel of TL2K critically passes under several sensitive structures, including the brick-lined Thameslink Tunnel. Over 100m of the Thameslink tunnel was considered to be potentially affected as the TL2K passed beneath at an angle of 21 degrees between the two alignments. Fig. 5 shows the crossing of TL2K underneath the Thameslink Tunnel with a surface line running above the ground. The minimum clearance is about 3.6m from the extrados of the new tunnels to the extrados of the brick-lined tunnel. Tunneling was conducted in stiff to very stiff London Clay using a semi-mechanized open shield TBM. It is important to note that a canal crosses the surface line close to the position of the TL2K tunnel. The canal basin is bounded on one side by a masonry retaining wall also shown in Fig. 5. Over a length of about 50m, this wall is founded directly on the underlying Thameslink Tunnel. This situation added further complication to the tunnel construction.

As part of the extensive monitoring program, optical fiber cables were attached at five cross sections and at three longitudinal sections (side walls and crown) of the old brick tunnel as shown in Fig. 6. Along the circumferential tunnel, attachment was made at eleven discrete sections. Fig. 7 shows the details of sensing fiber attachment along the circumference of tunnel. It was placed on the surface of the tunnel by spot gluing the cable at every steel hook that was drilled onto the brick-lined beforehand. The gluing was made once a pre-strain value of 0.2 - 0.3% was imposed on the optical fiber. This is done by manually hand-pulling the fiber between the first and the last fixed point of the encompassing sections. There are two reasons why pre-straining is needed: (i) to measure compressive strains (fibers which are slack will not show any compressive strain) and (ii) to identify the positions of the measured section along the fiber from the BOTDR readout. A base reading was also taken before the tunneling construction took place.

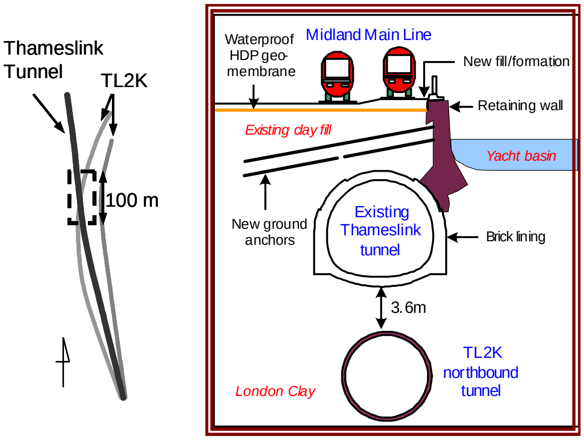


Figure 5 Thames Link Project

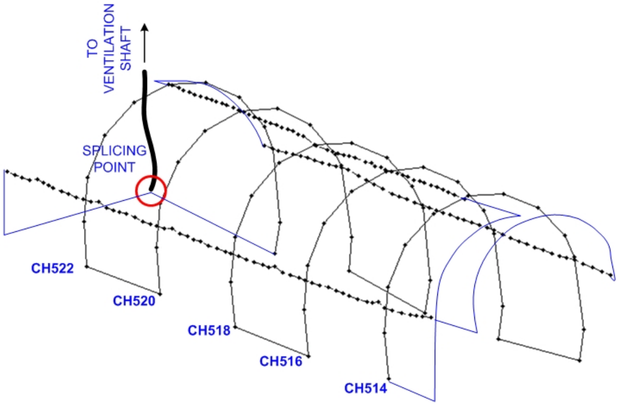


Figure 6 Layout of optical fiber attachment

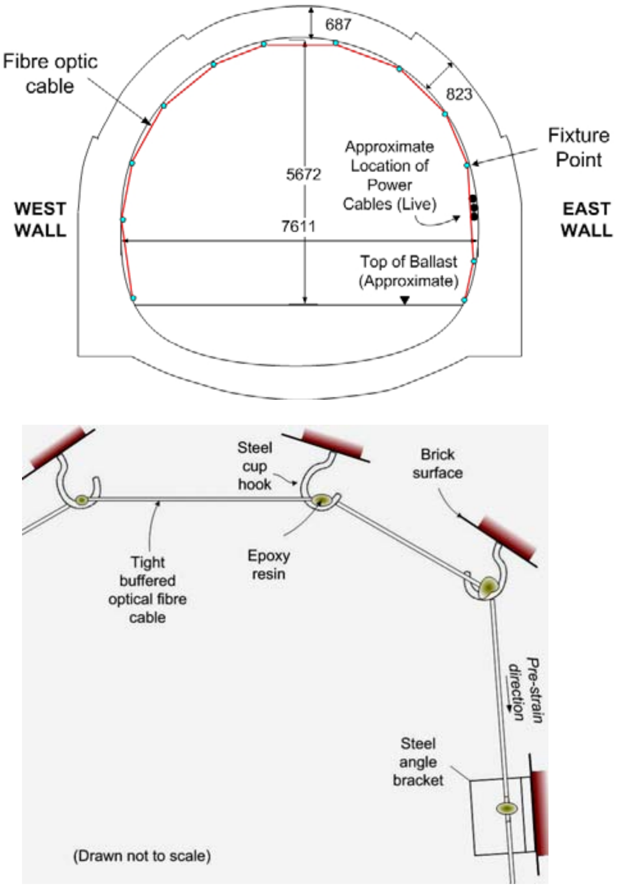
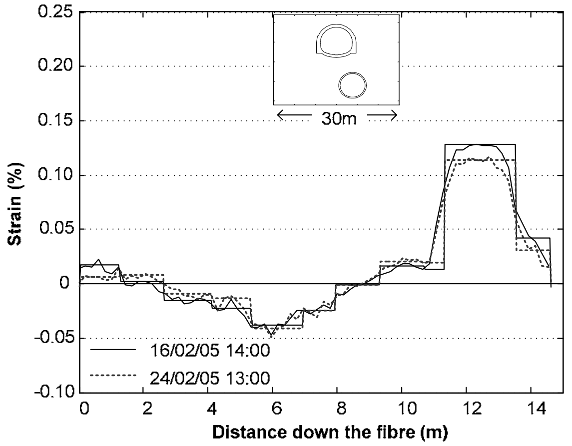
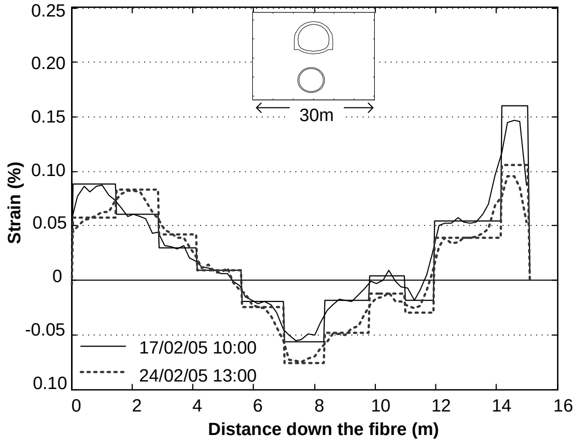


Figure 7 Optical fiber cable attachment along the circumference of the tunnel

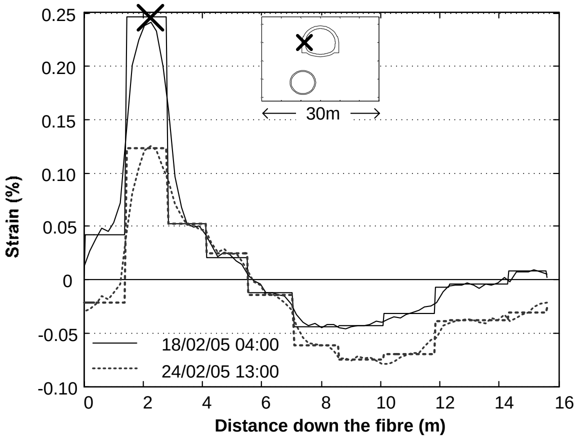
Figure 8 shows examples of the measured distributed strain data (CH516, CH518 and CH520; see Fig. 6). Measurement along the circumferential of the tunnel shows that the masonry structure elongated toward the new tunnel position. At the point of the exact crossover (CH518, Fig. 8b), a symmetric deformation is observed. At this cross section, both sides of the lining stretch while the crown compresses, indicating vertical elongation of the tunnel.



(a) CH520



(b) CH518



(c) CH518

Figure 8 Measured Distributed strains at three cross-sections

When the new tunnel moved away from the centerline of the old tunnel, the strain profile shifted. This is depicted in CH520 (Fig. 8a) where larger tensile strains are recorded in the east side of the lining where the new tunnel is positioned, while conversely in CH516 (Fig. 8c) larger tensile strains are recorded on the west side of tunnel (after the new tunnel crosses beneath).

A maximum tensile strain of 0.25% was recorded in CH516 (see Fig. 8c). At the west wall section of the masonry structure, the strain increased as the shield machine approached and a maximum tensile strain of 0.25% was recorded when the TBM had reached seven meters beyond the masonry tunnel. This highly localized strain however reduces to about 0.13% after the tunneling work completed. This indicates that the west wall side of the tunnel settled first as the tunnel was dragged toward the new tunnel. As the excavation continued and the volume loss increased, the east wall side then settled causing less strain in the west wall. The large strain occurred in CH516 was confirmed by the theodolite readings with some minor cracks reported. The final movements recorded in the existing tunnel were about 30mm settlement.

Figure 9 shows the longitudinal readings at four different positions of the TBM. As longitudinal movements along the old tunnel were an order magnitude smaller than cross-sectional movements, strain measurements obtained by BOTDR were as close as the system's accuracy permitted. However, it can be seen that there is a slight compression occurring at the position between CH520 and CH518 when the tunnel face is at position 2. In front of the tunnel face, there is a tensile strain section indicating hogging. The tensile strain section continued to develop in front of the TBM as it moved forward. The tensile strain immediately reduced from one fourth to half of the peak value after the TBM was located some four tunnel diameters away from the sensing point. The data demonstrates that the tunneling caused the crown of masonry tunnel to exhibit hogging in front of the tunnel face and sagging behind the TBM.

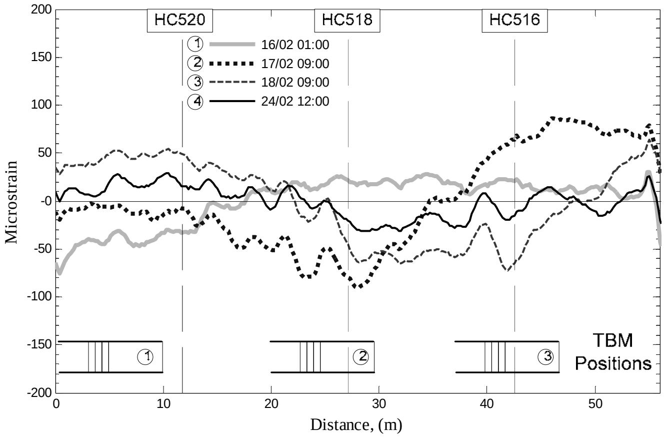


Figure 9 Longitudinal readings at the tunnel crown

The Thameslink Tunnel monitoring data provided an illustration of how an old tunnel behaves during construction of a new tunnel nearby. The distributed strain data showed the deformation mechanism in a clear manner. Further details of this work can be found in Mohamad et al. (2008).

CASE STUDY 2: MONITORING OF A SECANT PILED WALL

Distributed fiber optics strain measurement was conducted on a retaining wall constructed at a site in Chesham Place, London. The wall was constructed to allow ground excavation of a maximum depth of 10m supported up to four levels of braces to create an underground parking structure. The wall consisted of 450mm diameter hard-soft secant piles with male piles spaced at intervals of 0.6m providing the reinforcement. The female piles provided a temporary ground water cut off.

The bored piles were installed using temporary casings pushed into the clay to the toe of the male/female piles. Out of 192 male piles constructed across the perimeter of the wall, eight of them were equipped with inclinometer tubes while optical fiber strain sensors were installed in two piles.

By measuring strain along two fibers placed symmetrically with respect to the axis, it is possible to monitor the behavior of the retaining wall. The plane deformation problem of a pile with two fibers *a* and *b* is shown in Figure 10. By obtaining strains ε_a and ε_b shown in the figure and assuming that the wall is deforming elastically, one can derive the quantities of lateral component from Eq. 1, i.e. the curvature κ, the gradient α, and the lateral displacement *u*, while quantities for vertical component can be obtain from Eq. 2, consists of averaged axial strain and vertical displacement *w*.

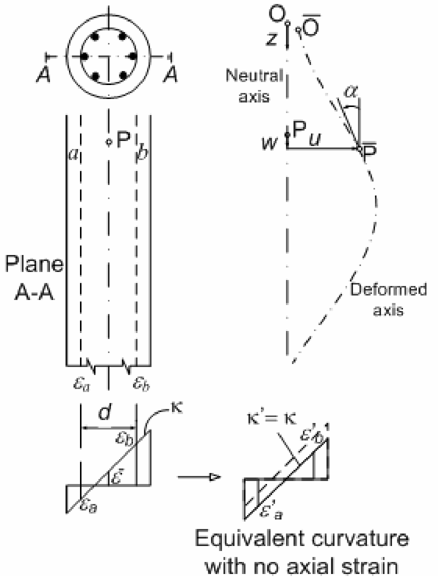


Figure 10 Monitoring lateral deflection of a pile

$$\kappa = \frac{1}{d}\left(\varepsilon_a - \varepsilon_b\right), \quad \alpha = \int \kappa dz + A, \quad u = \int \alpha dz + B \qquad (1)$$

$$\bar{\varepsilon} = \frac{1}{2}\left(\varepsilon_a + \varepsilon_b\right), \quad w = \int \bar{\varepsilon} dz + C \qquad (2)$$

The constants *A*, *B* and *C* can be found by taking further measurements such as measuring the pile tip displacements from theodolites or by considering known boundary conditions.

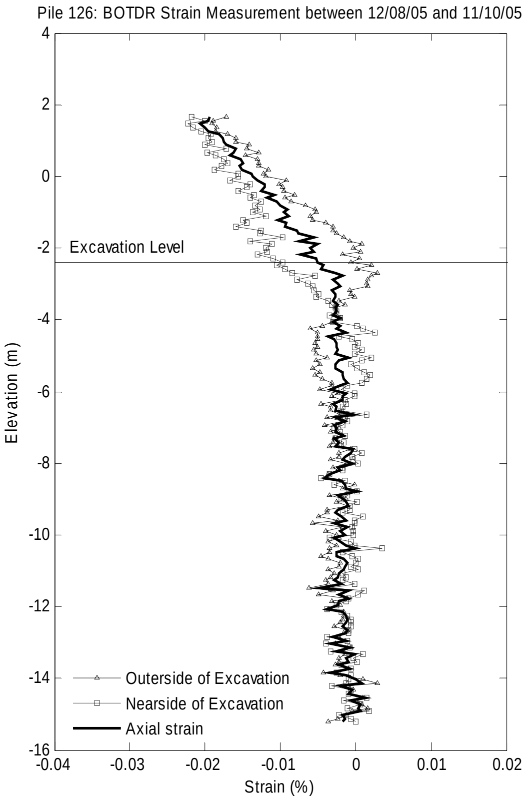
A special type of tight buffered cable was used (see Fig. 3c) so that it can withstand the harsh installation conditions, but is still sensitive to strain. The cable consists of four optical fibers that are reinforced with a pair of steel wires. Only one fiber is required for connection to the strain analyzer, the others provide redundancy.

A single optical cable was attached along two opposing sides of reinforcement cage by firstly fixing the cable with two clips at the bottom of the cage. The two sides of the cable were fed in as the cage was lowered into the borehole. Once the top section of the cage was positioned just above ground level, the two sections of the cable were pre-tensioned to about 2000με and clamped onto the adjacent bars. Concrete was poured into the casing to create bored piles.

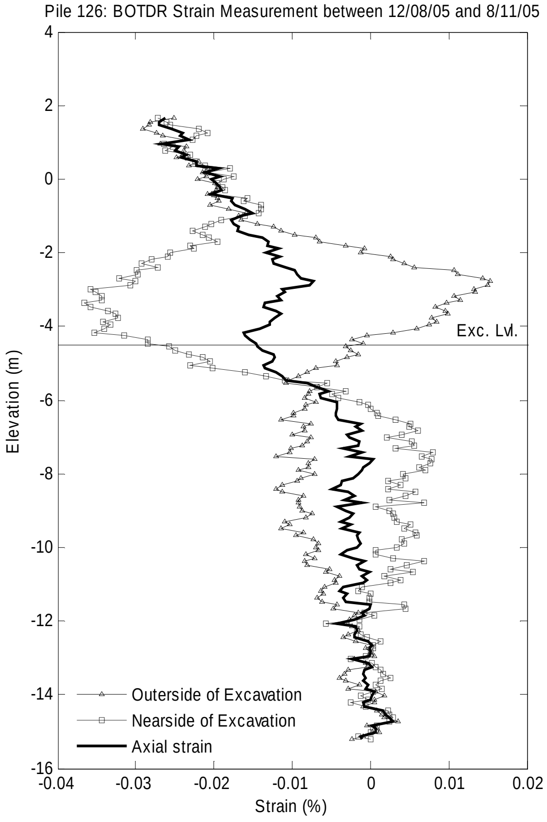
Two piles installed with optical fibers were monitored. In this paper, strain data from Pile 126 are presented. Further details of this case study can be found in Mohamad et al. (2007a). The measurements were made when the excavation depth was at -2.4m OD and at -4.5m OD. Fig. 11 shows the axial distributed strains deduced from the strain measurements of the two opposite side of the piles. The averaged axial strains indicate that the diaphragm wall was actually under compression especially above the ground level due to the existence of vertical loads at the top. There was an additional influence of temperature variance between the exposed pile and the embedded section.

Utilizing Eq. 1, strains measured from the two components of fibers as indicated in Fig. 11 can be converted into curvature. By integrating the curvature once, inclination of the pile can be deduced and by integrating it twice, lateral displacement of the pile is obtained. For simplicity, the piles instrumented were assumed not to move at the toe and therefore constants *A* and *B* were set as zero. For data comparison, inclinometer data obtained from the adjacent piles can be differentiated once to get the curvature and integrated once for lateral displacement.

Figures 12 show the comparisons between BOTDR and inclinometer readings from adjacent piles in terms of displacement and curvature at the excavation depths of -2.4m and -4.5m OD. The results indicate that the measurement of the basement wall deformation between BOTDR and inclinometer in terms of deflection and curvature are very much alike. The assumption of having no displacement and rotation at the pile's toe seemed to have matched both data

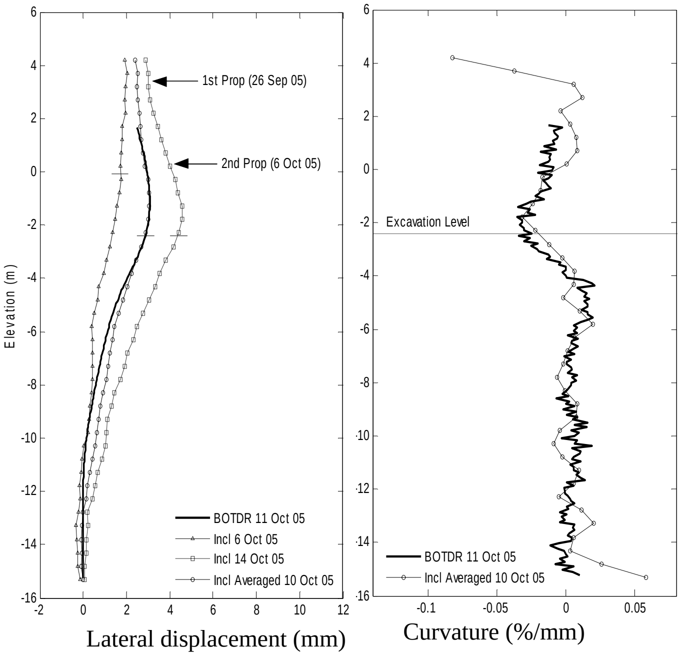


(a) Excavation depth -2.4 m

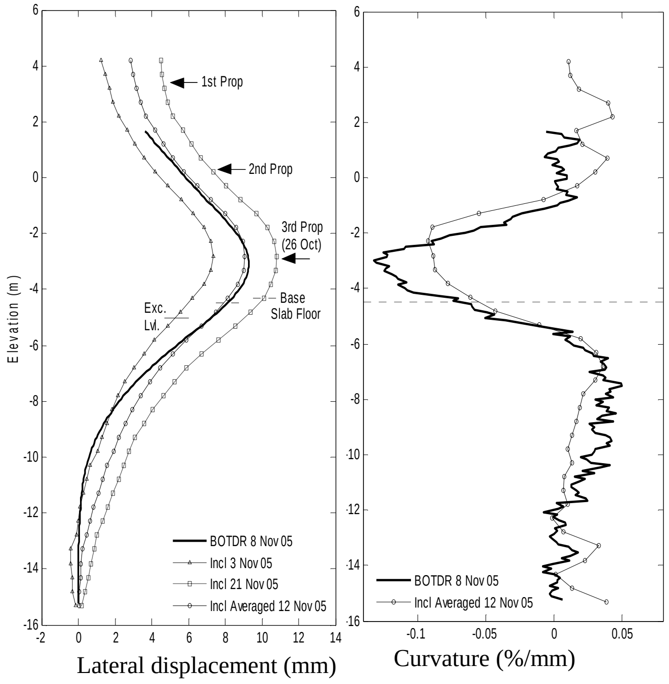


(b) Excavation depth -4.5 m

Figure 11 Distributed strain data on pile 216



(a) Excavation depth -2.4 m



(b) Excavation depth -4.5

Figure 12 Lateral displacements and curvatures, comparison between BOTDR data and inclinometer data

well. The maximum displacements were found at a depth of just above the ground level while the overall movements recorded throughout the whole stage of the construction fall within the acceptable designed range.

One of the main advantages of using BOTDR is that the strain measured in the piles would give a direct curvature/bending moment distribution. This is better than needing to differentiate the gradient from the inclinometer data. In terms of deriving the shear force diagram, inclinometer data has shown less stable results compared to the filtered BOTDR data especially in measuring small movements. On the other hand, the main concern of BOTDR strain sensing is the derivation of lateral displacement which involves acquiring two boundary conditions, i.e. the constants *A* and *B*.

The other benefit of having BOTDR as the tool to measure wall deflection is that the wall can still be monitored long after the construction of basement and ground floors since the optical fiber cables can be wired and accessed from different locations. Furthermore, the axial behavior of the wall can also be observed which is not possible when an inclinometer is used.

CONCLUSIONS

Because of the simple and quick installation technique, distributed optical fiber sensing can be as equally practical as the other conventional measurements. For extensive application to develop 'smart' geotechnical structures', in which strain measurement becomes more routine than at present, cost is particularly important. The cost of a standard optical fibre is very low (from $0.2/m) compared to other point measurement sensors. Most of the capital investment relates to the analyzer, which can be connected to a number of fibers or be shared at different sites. More choice from more manufacturers will give a reduction in price of analyzers. It has considerable potential as a system for long-term monitoring.

There are other possibilities of using the distributed strain measurement technology for other geotechnical structures. Other works at Cambridge University on BOTDR monitoring, which was not presented in this paper, are the following.

- Monitoring of axial behavior of piles (Klar et al., 2006; Bennett et al., 2006).
- Monitoring of water main pipeline during construction of a tunnel underneath (Vorster et al., 2006).
- Monitoring of twin tunnel construction monitoring in Singapore in collaboration with the Land Transport Authority (Mohamad et al., 2007b).
- Monitoring of clay cuttings and embankments along London's Ring Motorway (Janmonta et al., 2008).
- Monitoring of soil nails for stabilizing steep highway curt slope (Amatya et al., 2008).

There are a number of benefits to new innovative sensor technologies; the most obvious one is the increased safety levels they can provide to cope with adjacent new constructions and with natural disasters such as climate change, flood warnings and earthquakes. Furthermore, these technologies will also be able to reduce costs associated with end-of-life structures. They help us to know "What (is happening)" to our geotechnical structures, so that we can address the question of "why" in order to better understand the behavior of geotechnical structures.

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