Fibre optic installation techniques for pile instrumentation

Techniques d'installation de fibres optiques pour pile instrumentation

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ABSTRACT

An innovative technique based on optical fibre sensing that allows continuous strain measurement has recently been introduced in structural health monitoring. Known as Brillouin Optical Time-Domain Reflectometry (BOTDR), this distributed optical fibre sensing technique allows measurement of strain along the full length (up to 10km) of a suitably installed optical fibre. Examples of recent implementations of BOTDR fibre optic sensing in piles are described in this paper. Two examples of distributed optical fibre sensing in piles are demonstrated using different installation techniques. In a load bearing pile, optical cables were attached along the reinforcing bars by equally spaced spot gluing to measure the axial response of pile to ground excavation induced heave and construction loading. Measurement of flexural behaviour of piles is demonstrated in the instrumentation of a secant piled wall where optical fibres were embedded in the concrete by simple endpoint clamping. Both methods have been verified via laboratory works.

RÉSUMÉ

Une technique innovatrice basée sur la détection par fibre optique permet la mesure continue de contrainte a été récemment introduite pour le monitorage des structures. Connue en tant que réflectométrie optique de Temps-Domaine de Brillouin (BOTDR), cette technique de détection distribuée par fibre optique permet la mesure de la contrainte sur toute la longueur (jusqu'à 10km) d'une fibre optique convenablement installée. Des exemples des réalisations récentes de la détection BODR par optique de fibre dans les piles sont décrits en cet article. Deux exemples de la fibre optique distribuée détectant dans les piles sont démontrés utilisant différentes techniques d'installation. Dans une pile porteuse, des câbles à fibres optiques ont été attachés le long des barres de renforcement par collage par points équidistants pour mesurer la réponse axiale de la pile au chargement de poussée induit par excavation au sol et de construction. La mesure du comportement flexible des piles est démontrée dans l'instrumentation d'un mur empilé sécant où des fibres optiques ont été enfoncées dans le béton par le fixage simple de point final. Les deux méthodes ont été vérifiées par l'intermédiaire des travaux de laboratoire.

Keywords : Performance monitoring, deep foundations, retaining structures, BOTDR

1 INTRODUCTION

Structural integration of fibre optic sensing systems represents a new branch of engineering which involves the unique marriage of: fibre optics, optoelectronics and composite material science. Optical fibre sensors have a number of advantages over their electrical counterparts. The transmission of light down an optical fibre is an established technique in optical communications for carrying information and is the primary candidate for resident sensing systems. Fibre 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 fibre optics utilizing Fibre 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, the applications of a unique fibre optics technology called the ‘Brillouin optical time-domain reflectometer (BOTDR)’ to monitor the performance of a load bearing pile and multi-propped diaphragm wall are presented. The novel aspect of this new technology lies in the fact that tens of kilometres of fibre can be sensed at once for continuous distributed strain measurement, providing relatively cheap but highly effective monitoring systems.

This paper demonstrates the two different optical fibre installation methods developed during the research study, i.e. *spot-glued* and *end-clamped* (between the optical cables and the steel reinforcements). The methods were developed to suit the practicality of installation. A brief presentation of the data and its interpretation are included in this paper.

2 FIBRE OPTIC STRAIN SENSING USING BOTDR

When a pulse of light that travels down an optical fibre, the majority of light travels through but a small fraction is scattered back at every location of the fibre. The frequency of this

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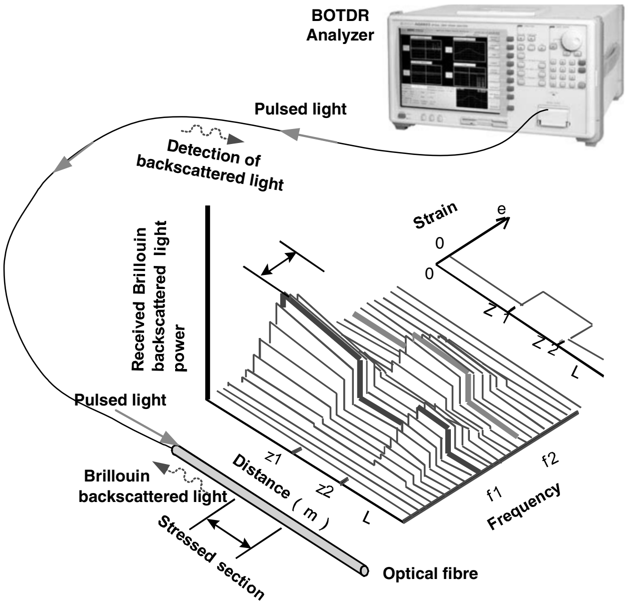


Figure 1. BOTDR system

backscattered light is shifted from the original input frequency by an amount linearly proportional to the temperature and strain applied at the scattering location (see Fig. 1). By resolving the back-scattered signal in time and frequency, a complete strain profile along the full length of the fibre can be obtained (e.g., Horiguchi et al. 1994).

A particular advantage of optical fibre technology comes from the low propagation losses that can be obtained with a single mode optical fibre. This means that strain can be measured along the full length (up to 10km) of a suitably installed optical fibre by attaching a BOTDR analyzer to one end (see Fig. 1).

A simple optical fibre that can be used for BOTDR is shown in Fig. 2a. It has an external diameter of 0.9 mm with a single optical fibre 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 (~US$0.20/meter) is fragile and care must be taken when installing it.

Extra layers of protection are often placed around more than one fibre to form a cable. Special strain sensing optical fibre cables are also available. An example of such fibres is shown in Figs. 2(b) and (c). It is reinforced by steel wires and Kevlar yarns. These are more robust, but still transmit the strain applied through to the glass optical fibre and allow the strain to be measured. Although this is considerably more expensive (up to US$20/m), it is likely to be faster to install as they do not require such gentle handling (like for cast-in-place piles).

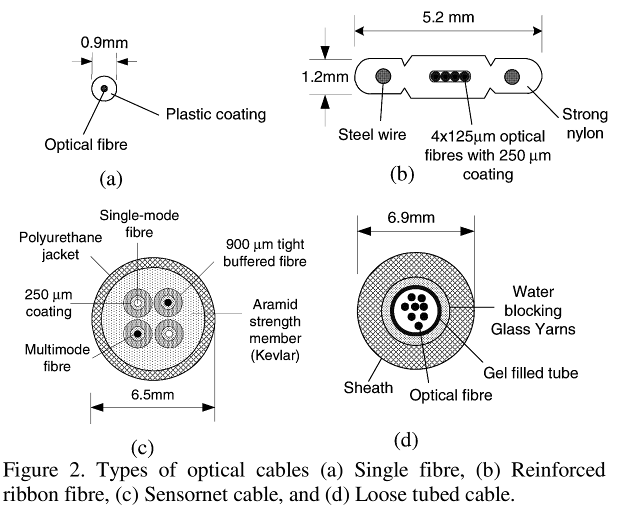


Figure 2. Types of optical cables (a) Single fibre, (b) Reinforced ribbon fibre, (c) Sensornet cable, and (d) Loose tubed cable.

More robust forms of standard telecom cables have thick plastic coatings, sometimes reinforced with steel, around a gel filled tube containing the optical fibres (as shown in Fig. 2d). This makes these cables unsuitable for strain sensing as the optical fibres 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 (~US$1/m). It can also serves as a temperature monitoring cable.

3 BANKSIDE, LONDON

Study on the performance of a load bearing pile during a live construction project was conducted at Bankside 123, a major office development located on the south bank of the River Thames in London (Bennett et al. 2006). The office building consisted of 12 level floors with three basement levels supported by 67 very high capacity piles with diameters ranging from 1.2 m to 2.4 m and founded in Thanet Sands of up to 53 m. The basement was formed in a partial top-down construction with piles and plunge columns installed from the first basement level. This allows simultaneous construction of ground floor slab at the top and further excavation below the first basement level. A typical cross-section of the foundation is shown in Fig. 3.

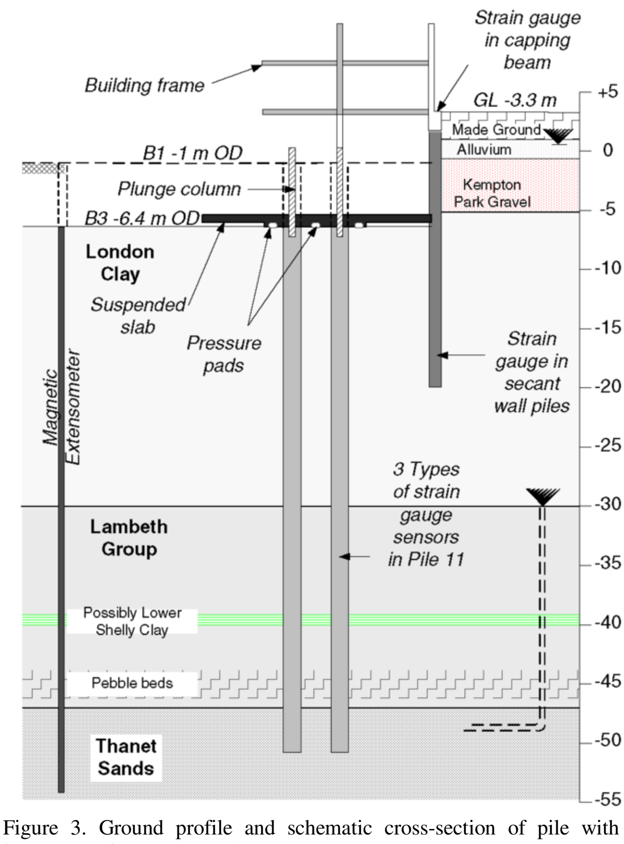


Figure 3. Ground profile and schematic cross-section of pile with instrumentation (Mohamad 2008).

Four different types of optical fibre cables were used as part of the BOTDR sensing system. The strain sensing cables consist of Single fibre (Fig. 2a), Reinforced-ribbon (Fig. 2b) and Sensornet (Fig. 2c), whereas the Unitube-armoured cable (Fig. 2d) was used as the wiring cable to connect the sensing cables to the optical strain analyser above the ground. As the pile is very long i.e. ~50 m depth, reinforcement cage had to be assembled from three separate sections during pile construction. To ease the pile construction process, all of the instrumentation were installed when the cages were laid horizontally on the ground surface and before the insertion of cage into the borehole. Optical fibres were attached onto the reinforcement section by firstly pre-straining the fibres under tension before spot-gluing at every 100–200 mm onto the steel bars. The optical cables were installed on two sides of the cage to form one complete loop so that the cables can be access from both ends if required. It also creates redundancy to the measurement. At the end of the sensing sections, the fibres were loosely coiled inside a secured box to allow temperature compensation (the box also served as a protection zone when two different fibres were joined together). Further explanation on temperature compensation method including the appropriate values used for optical cables thermal expansion coefficients are described in Mohamad (2008).

Fig. 4 compares strain measurements from the three independent monitoring systems; BOTDR (Bennett et al. 2006), FBG (Kister et al. 2007), and VWSG (Bourne-Webb et al. 2006) as well as RATZ (Randolph 2003) analysis. Two different stage of pile strain distribution are presented;

- Fig. 4a: *Completion of Basement 3 slab*,
- Fig. 4b: *Completion of all building frames*.

It can be seen in Fig. 4 that all instrumentation are broadly comparable, although the difference in the magnitude is reflected by the lagging of baseline readings. For example, FBG recorded largest compressive strain while VWSG which missed the loadings from the first two construction stage recorded the smallest strain.

Strain data immediately after the basement excavation is presented in Fig. 4a. Measurements show very little tensile strain recorded near the bottom of the shaft. The pile mainly experienced compression with strain decreasing along the pile depth. This is mainly because the undrained type of London Clay where the ground did not immediately heave right after the basement excavation as recorded by the extensometer data (not included here). The load-transfer analysis shows that, at this period of construction stage, the pile experienced only minor compression of less than 50 $\mu\varepsilon$ from the head loading of ~2500 kN.

Although the general trend shows the pile was compressing all the way to the base, there were several distinctive localised tensile strains recorded by BOTDR near the bottom of the shaft probably associated with the initiation of tensile cracks. Such strain profile in the proximity of hard stratum of Lambeth Group may indicate there were development of relatively high shaft frictions within these layers which restrained the shaft from elongating due to the existence of heave force.

In Fig. 4b, pile underwent larger compressive strain as more loadings were applied. BOTDR and FBG recorded compressive strain of about 150 $\mu\varepsilon$ near the top shaft with very little load reaching the bottom shaft. Interestingly at this moment, a maximum heave movement of up to 30 mm near the pile tip was recorded by the extensometer. However, according to the theoretical curve (RATZ) which matches with the observed value using relatively small soil shear modulus, the large heave movement actually generated only small tensile force component that is easily eliminated by the greater compression load in the pile.

In general, the instrumented pile was observed to be under compression even when there was considerable amount of ground heave recorded (i.e. 30 mm at ground level). This is because of the continuing rise of structural loading at the top as well as the ground conditions of the site, in this case, probably consisting of soils with relatively low shear modulus. From the theoretical examination (where the result matches with fibre optic data), soil with low shear modulus generates only a small amount of heave force component.

4 CHESHAM PLACE, LONDON

Distributed fibre 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 fibre strain sensors were installed in two piles.

By measuring strain along two fibres placed symmetrically with respect to the axis, it is possible to monitor the behaviour of a retaining wall. The plane deformation problem of a pile with two fibres *a* and *b* is shown in Fig. 5. By obtaining strains ε_a and ε_b shown in the figure, 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.

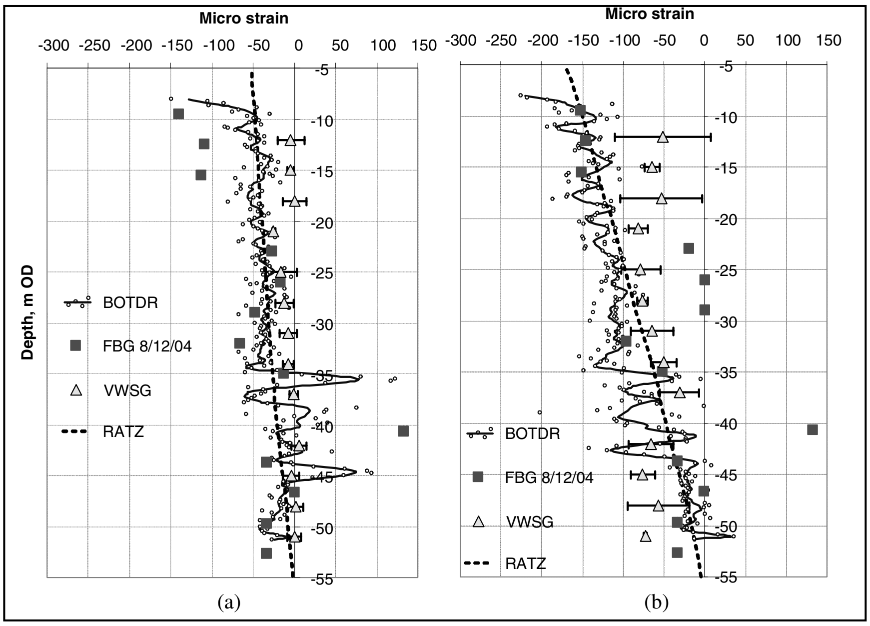


Figure 4. Compressive strains measured when building load approximately at (a) 2500kN, and (b) 7500 kN (Mohamad 2008).

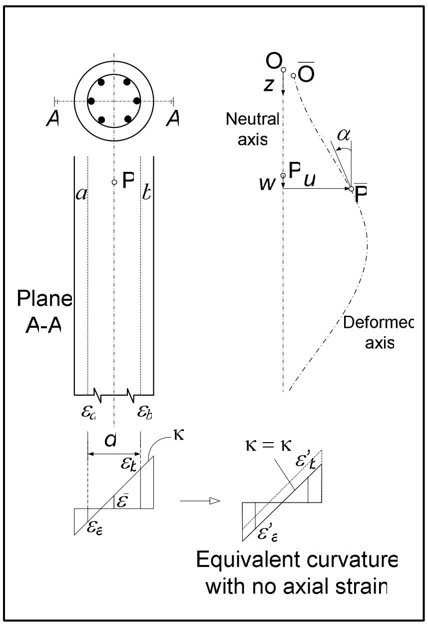


Figure 5. Monitoring lateral deflection of a pile.

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

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

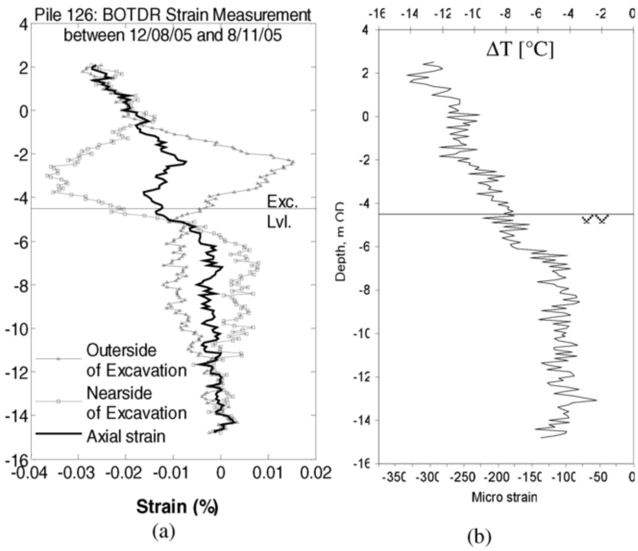
The constants A, B and C can be found by taking further measurements such as measuring the pile tip displacements from theodolites or by considering known boundary conditions.

A single optical cable (Fig. 2b) 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 $2000\mu\varepsilon$ and clamped onto the adjacent bars. A single loose-tube cable (Fig. 2d) was also inserted into the pile to measure the temperature distribution of the pile. The concrete was then poured into the casing to create bored piles.

Two piles installed with optical fibres were monitored. In this paper, strain data from Pile 126 when the excavation depth was at -4.5m OD is presented. Further details of this case study can be found in Mohamad et al. (2007) and Mohamad (2008). Fig. 6a 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. This was due to the influence of temperature variance of up to 5 °C between the exposed pile and the embedded section as shown in Fig. 6b.

Utilizing Eq. 1, strains measured from the two components of fibres as indicated in Fig. 6a 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. The data was compared to the inclinometer data obtained from the adjacent piles are shown.

Fig. 7 shows the comparison between BOTDR and inclinometer readings from adjacent piles in terms of displacement and curvature. 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 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.



(a) (b)

Figure 6. (a) Distributed strain data from sensing cable, and (b) Thermal strain from loose tube cable (Mohamad 2008).

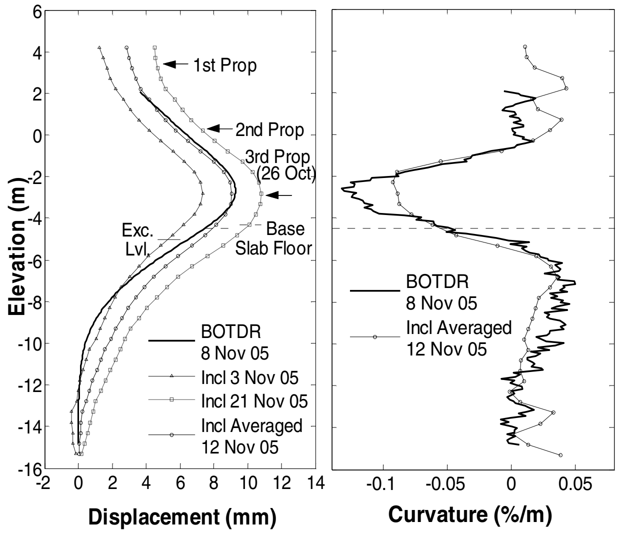


Figure 7. Lateral displacements and curvatures, comparison between BOTDR data and inclinometer data

5 CONCLUSION

Distributed optical fibre sensing in piles were successfully demonstrated using two installation techniques, fixed-point-method for load bearing pile and end-clamped technique for secant-piled wall. Optical fibres were able to measure both axial and lateral deformation by measuring strains from a single optical fibre placed along two sides of the structure's plane. Local features such as cracking were also detected in the bored pile. The performance of the proposed installation methods have also been verified in the laboratory works (Mohamad 2008).

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