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INNOVATIVE STRUCTURAL HEALTH MONITORING OF FOUNDATION PILES USING DISTRIBUTED FIBRE-OPTIC SENSING

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Abstract: Tall buildings in congested urban areas need deep pile foundations to carry the huge building and operational loads. The current state-of-the-art design of foundation piles is based on previous knowledge gained from small-scale laboratory tests and some instrumented field tests. In some cases the as-built pile might be different from the initial design because of various construction constraints, which might result in a smaller pile capacity. Also, pile bearing capacity may be compromised over time because of material strength degradation or additional unexpected loads. It is therefore essential that we monitor the response of foundation piles in the future so that we are able to assess their structural health and take necessary engineering remedial actions on time.

Distributed fibre-optic strain sensing using BOTDR or BOTDA is a novel instrumentation technique that offers a spatially-continuous data. An optical fibre cable is installed along the depth of the pile which serves as a sensor itself, as it provides distributed strain data every 5-10cm along the cable length. This is superior to more conventional discrete point-based sensors which provided limited monitoring information at pre-specified location points. The availability of a distributed strain regime offers a number of advantages when it comes to studying soil-structure interaction problems such as foundation piles.

This paper describes the use of distributed fibre-optic sensing in monitoring foundation piles and presents some recent case studies in London. The monitoring data is also complemented by relevant finite-element pile models that are able to reproduce the response of the examined foundation piles.

Keywords: structural health monitoring; fibre-optic strain sensing; foundation piles; finite-element analysis

1. Introduction

Instrumented pile load tests are used widely to establish relevant geotechnical parameters for foundation piles, such as the ultimate bearing capacity, or shaft and base resistance. Traditionally, pile load tests were monitored with a number of discrete point sensors, such as vibrating-wire-strain-gauges (VWSGs). Although these kind of sensors have been proved to be accurate and reliable they still lack in term of continuity of the data. That is because they provide discrete values of strain, i.e. only at the point where the VWSG sensor is installed.

In many cases of complicated soil-structure interaction, a spatially-continuous profile along the entire length of the pile is very useful in illustrating some finer details of the performance of the pile, such as necking,

strain localisation, abnormal pile diameter etc.

Recent developments in optical strain sensing, such as the Brillouin Optical Time-Domain Reflectometry (BOTDR) or Analysis (BOTDA) offer the opportunity to obtain distributed values of monitored strain. Fibre optic strain sensing provides a wealth of information that is very useful in understanding the actual behaviour of piles.

This paper presents the method of distributed fibre optic sensing and its application in monitoring pile foundations. The principle of the method is first introduced and then a recent example of a relevant application is presented.

2. Distributed fibre optic sensing

This section provides a brief description of the principles of BOTDR/A. The complete description of the physical principle (i.e.

theoretical physics, photonics and optics) and the relevant experimental approaches followed for calibration are not included, as they can be found elsewhere (Horiguchi et al. 1995) (Mohamad 2007) (Iten 2011) (Soga 2014) (Soga et al. 2015). A detailed description of the theory of distributed FO strain sensing and its applications in civil and geotechnical infrastructure is given by Kechavarzi et al. (2016), whereas examples of application to foundation piles are given by Klar et al. (2007), Ouyang et al. (2015) and Pelecanos et al. (2016, 2017a, 2017b) and energy piles by Ouyang et al. (2018a,b,c). More examples on monitoring soil-structure interaction may be found by Acikgoz et al. (2016, 2017), Cheung et al. (2010) Di Murro (2016), Schwamb et al. (2014) and Soga et al. (2017).

2.1 Principle of BOTDR/A

A fibre optic (FO) cable allows light waves from a FO analyser to travel along its entire length through total internal reflection. This allows a signal to be carried over very long distances, similar to broadband Internet. Backscattered signals are generated as the light wave passes through the optical fibre and presents itself as Rayleigh, Raman and Brillouin spectrum. Within the Brillouin backscatter, the peak frequency experiences a shift that is considered to be linearly proportional to applied strain. Using the measured time required for the backscattered signal to return to the analyser, the specific location at which this frequency shift is observed can be estimated accurately. Therefore, the entire fibre optic cable is practically serving as a distributed strain sensor.

The FO analyser sends a light with of 1550 nm wavelength into an optical fibre and the generated Brillouin spectrum of the back-scattered light has 25-27 MHz bandwidth and around 11 GHz central peak frequency when no strain is applied on the fibre. The back-scattered Brillouin central frequency, ν_b , is related to the input light according to Eq. 1 and this is provided directly from the FO analyser.

Changes in temperature and/or strain induce a density change in the cable and therefore change in the acoustic velocity, ν_a , of the light too. As the strain or temperature at a given location change, the frequency of the backscattered light is shifted by an amount which is approximately linearly proportional to the applied strain, $\Delta\varepsilon$, or temperature, ΔT .

Therefore knowledge about of this frequency difference can provide information about the applied strain and temperature changes at the location where the back-scattered light was generated. As the speed of light is constant, the location can be evaluated by measuring the time since the light was initially sent into the fibre. Back-scattered light is generated at every point along the entire length of the fibre and therefore by resolving both time and frequency a continuous strain profile along the fibre can be determined.

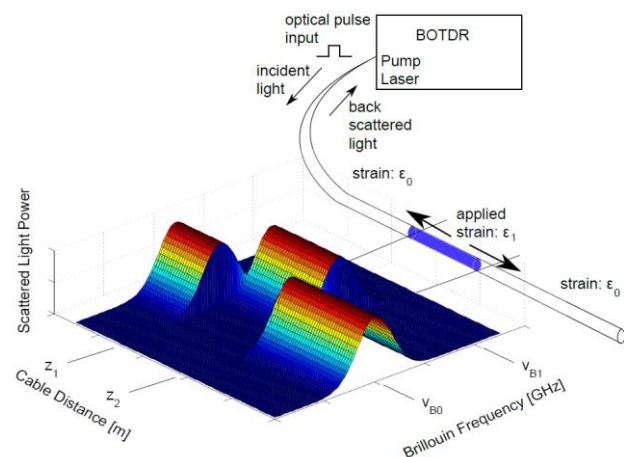


Figure 1: Principle of BOTDR/A.

2.2 Fibre Optic cables

Strain on an optical fibre can be generated from two sources, mechanical or thermal. Therefore, two types of optical fibre cables are installed and are shown in Figure 2: Fujikura 4-core single mode fibres reinforced ribbon cable for strain sensing (strain sensing cable) and Excel 8-core single mode fibres loose tube for temperature compensation (temperature cable). While they are both attached to the reinforcement cage, the fibre optic cores of the temperature cable sit in a gel which isolates any transfer of mechanical strains from the outer coating. Thus it is only subjected to thermal

changes. These measurements are used to compensate the readings measured from the strain cables to provide an accurate reading of interest, the actual mechanical strain.

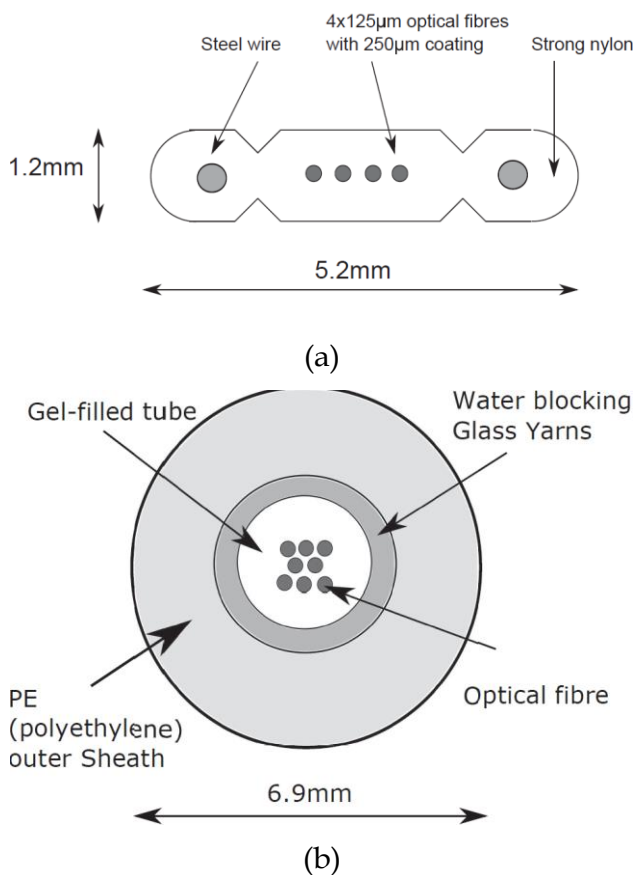


Figure 2: Fibre Optic cables: (a) strain cable, (b) temperature cable.

2.3. Sensor installation

Installation of FO cables is usually done on site. Long pile foundations typically consist of a number of steel reinforcement cage segments and therefore the bottom steel cage is instrumented on the ground. The FO cables are running along the entire length of the bottom segment on two opposite sides of the pile and a loop of some FO cable is made close to the bottom of the segment. The longitudinal cables are pre-strained (i.e. a tensile strain is applied) using cable clamps at the two ends of the steel cage. Once the borehole is dug, the bottom cage is inserted and while the other cages are spliced onto the bottom cage and the whole pile lowered down in the borehole, the remaining FO cable is attached to them. Finally, the two ends of the FO cable run from the top of the pile to the FO analyser.

With the pile loaded axially, it is assumed that the concrete pile will have negligible hoop strain across its cross section and therefore a 10m loop cable for both strain and temperature is prepared and secured at the end of the bottom reinforcement cage to serve as a zero-strain loop for referencing and compensation purposes.

For the ease of data interpretation, a pre-strain of about 1000-2000µε is often introduced to the strain cable. Anchorage is provided on the bottom loop end by cable wire clamps before stretching the strain cable to the predetermined pre-strain. Strain cable is then secured with another set of cable wire clamps at the top of the reinforcement cage before supplementing the anchorage by either spot gluing with epoxy glue or using cable ties at approximately every 0.5-1.0m interval. Temperature cables are loosely secured next to the strain cables with cable ties as they are routed to the top of the cage.

Once the bottom cage has been instrumented, it is lowered into the borehole. The fibre optic cables are then unwound from the reels on each side of the borehole as the cage is lowered. Pre-straining is carried out for the strain cables for subsequent reinforcement cages as well without epoxy glue due to time constraints. Concrete is subsequently poured in the borehole and as the concrete cures the FO cables become securely embedded within the pile. Further details of FO cable installation in piles established at the University of Cambridge can be found in (Klar et al. 2006), (Soga 2014) and (Soga et al. 2015).

2.4. Fibre Optic data analysis

Measuring the Brillouin frequency difference, one can obtain the applied strain on the cable. FO cables are able to detect strains due to both mechanical and thermal loads, the two components can be analysed separately. The measured frequency difference from the "temperature cable", $\Delta\nu_{BT}$, is influenced only by changes in temperature, whereas that from the "strain cable", $\Delta\nu_{BS}$, is influenced by changes in both mechanical load and temperature.

ICSECM2017-Paper120

Therefore, changes in temperature, ΔT , can be obtained from Eq. 1 (where, C_{TT} is a property of the cable, obtained by calibrating the "temperature cable", which determines how temperature affects the Brillouin frequency reading of the cable and it is usually around $1.1 \cdot 10^{-3}$ GHz/°C).

$$\Delta T = \frac{\Delta v_{bT}}{C_{TT}} \quad (1)$$

The thermal strain, ε_{temp} , (the strain that corresponds to free thermal expansion strain due to temperature change) is then given by Eq. 2 (where, α_c is the thermal expansion coefficient of concrete and it is usually around $9.65 \mu\epsilon/^\circ\text{C}$).

$$\varepsilon_{temp} = \alpha_c \cdot \Delta T \quad (2)$$

The real (observed) strain, ε_{real} , (the actual strain that the pile experiences in the field) is then given by Eq. 3 (where, C_E is a property of the fibre, obtained by calibrating the "strain cable", which determines how strain affects the Brillouin frequency and it is usually around $5 \cdot 10^{-4}$ GHz/ $\mu\epsilon$; and C_T is a property of the fibre that determines how the Brillouin frequency is affected by temperature difference, and it is usually around $1.0 \cdot 10^{-3}$ GHz/°C).

$$\varepsilon_{real} = \frac{1}{C_E} (\Delta v_{bS} - C_T \cdot \Delta T) \quad (3)$$

The mechanical (constrained) strain, ε_{mech} , (the reaction strain that is the result of both the applied mechanical load and temperature) is then given by Eq. 4

$$\varepsilon_{mech} = \frac{1}{C_E} \left[\Delta v_{bS} - C_T \cdot \frac{\Delta v_{bT}}{C_{TT}} \right] - \alpha_c \cdot \frac{\Delta v_{bT}}{C_{TT}} \quad (4)$$

3. Application

This section provides a recent application of the BOTDR/A method to monitor a pile load test in London.

3.1. Description of pile load test

This project in London was designed to house a fourteen-storey office building with two basement levels. A number of mini piles of 0.305m diameter were constructed in close proximity to support the superstructure. A high-strength steel reinforcing case was

inserted in the ground after the drilling process. The pile tested is 0.305m diameter (0.343m at the top 6m because of a steel casing around the pile) and 25m long, as shown in Figure 3 (a). On the same figure, the soil stratigraphy is also included with some known material properties obtained from relevant triaxial and simple shear laboratory tests. The pile test was carried out once the concrete material achieved a specified value of minimum strength. The pile test consists of three consecutive cycles of applied load (at the top of the pile) of up to 720kN, 1080kN and 1985kN for each of the three cycles, achieved after several loading and unloading steps (Figure 3 (b)). The pile was instrumented with distributed FO cables on two opposite sides of the pile and a number of discrete VWGS along the pile depth.

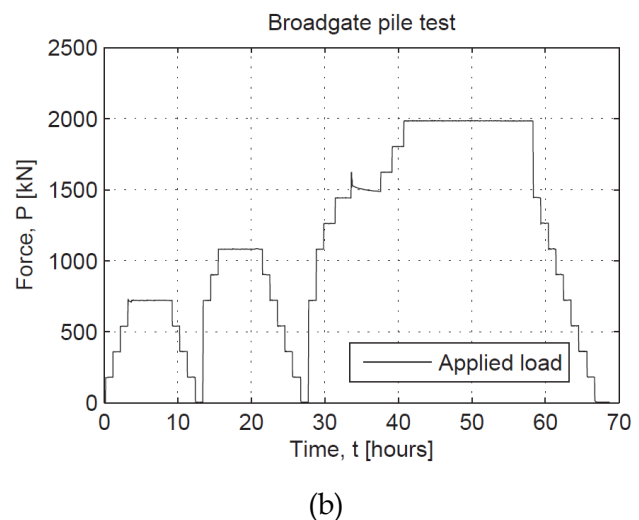
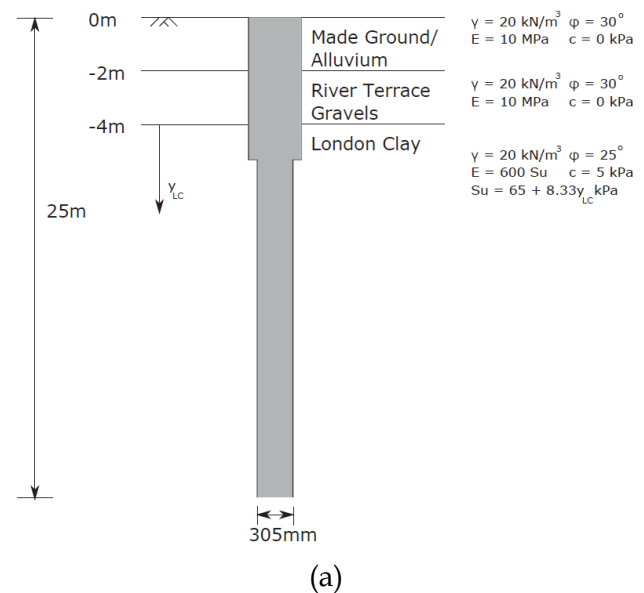


Figure 3: Pile load test: (a) geometry of the pile and soil stratigraphy, (b) history of applied load.

3.2. Fibre optic monitoring data

Figure 4(a) shows the axial strain in the pile for the three peak values of the three cycles as it was captured by the FO cables and the VWSGs, whereas Figure 4(b) shows the corresponding axial force profiles (calculated from strains multiplied by the pile axial rigidity, EA, as described by Eq. 7 and using $E=30000\text{MPa}$). No VWSG data were obtained for the largest cycle (i.e. for loading of 1985kN), as there was a malfunction of the VWSG instruments, and therefore only FO data is available for this load case. It is also shown that there is some scatter in the FO data values which is currently a known issue with distributed FO strain sensing systems. This is because the standard resolution of FO is constant and about $30\text{-}50\mu\epsilon$ and therefore this becomes relatively less significant for larger applied loads (which imply larger induced strains). The waviness of FO strains may offer a challenge when differentiating strain data profiles to obtain shaft friction values, but their spatial continuity allows for a distributed sensing of localised strains, e.g. necking, fracture etc., whereas, such localised features would not be identified by discrete monitoring systems (such as VWSGs). Figure 4(c) shows the vertical displacements, u , of the pile from the FO cables. The values from the FOs were obtained by integrating the strain profiles and adding those to absolute displacement measurements from displacement transducers at the top of the pile.

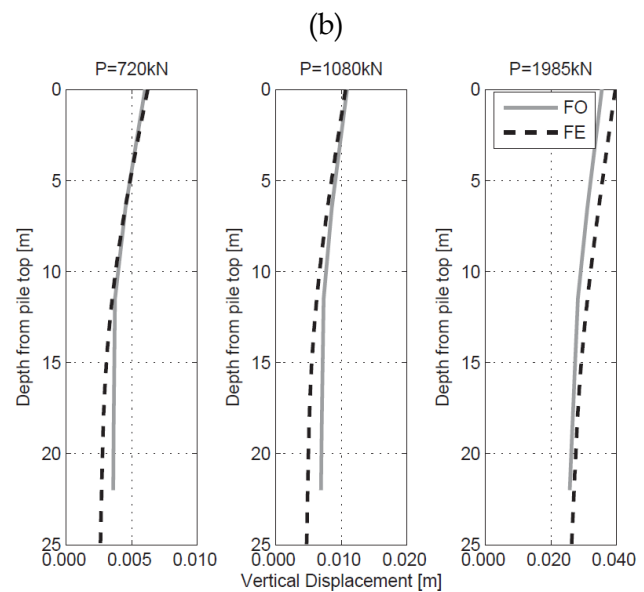
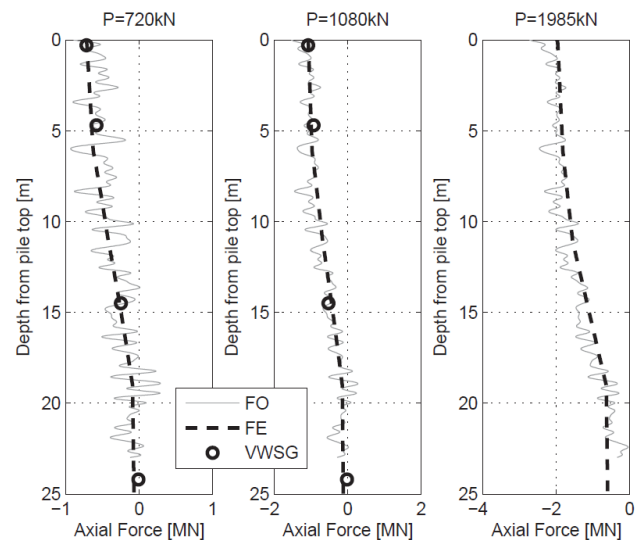
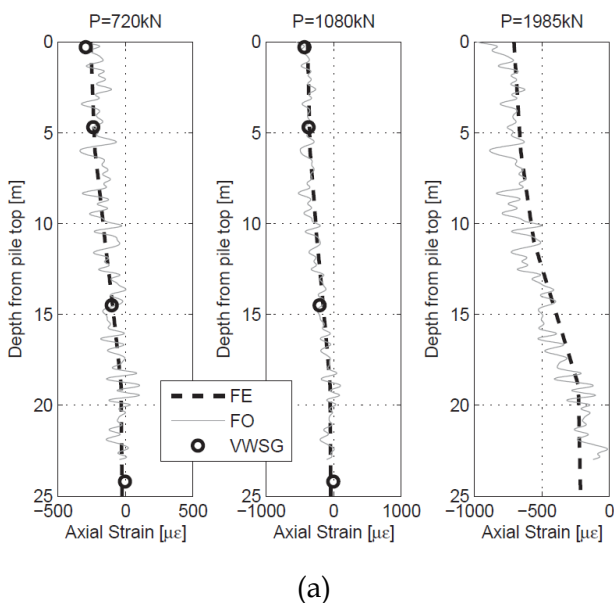


Figure 4: Monitoring data: profiles of (a) axial strain, (b) axial force and (c) vertical displacement.

The results of a simplified numerical finite element (FE) beam-spring model are included for comparison in all profiles in Figure 4. The simplified FE analysis considered a single vertical pile loaded axially from the top modelled with linear beam elements and represented the surrounding soil with nonlinear springs which is a practical approach as opposed to the more common way of modelling the soil with solid elements. The nonlinear springs follow a 4-parameter load-transfer curve (t - z), as described by Eq. 5, (where t_m and k_m are dependent on geotechnical properties and are related to the maximum soil stiffness and shaft capacity

respectively, whereas parameters d and h are related to degradation of soil stiffness and hardening).

$$t = \frac{k_m \cdot z}{d \sqrt{\left[1 + \left(\frac{k_m}{t_m} \cdot z \right)^{(h \cdot d)} \right]}} \quad (5)$$

All the beam elements and non-linear springs contribute to the global stiffness matrix (which is a sum of the pile stiffness matrix, K_p , and the soil stiffness matrix, K_s) and therefore the global FE equilibrium equations, as described in Eq. 6. Due to the nonlinear nature of the soil-spring the external load, P , is applied incrementally and the solution provides the nodal displacements, u . More details about the numerical model may be found from Pelecanos et al. (2017b) and Pelecanos & Soga (2017a,b, 2018).

$$([K_p] + [K_s]) \cdot \{u\} = \{P\} \quad (6)$$

It is shown from Figure 4 that the FE model is able to reproduce the observed profiles of axial strain and force and vertical displacement very well. This suggests that the FO strain data were able to provide a very good insight into the real performance of the monitored pile and that they can be reliably used in the future to establish the response of foundation piles.

4. Conclusion

This paper presents the principle of distributed fibre optic sensing using the Brillouin Optical Time Domain Reflectometry (BOTDR) or Analysis (BOTDA) method and its application on monitoring foundation piles. A recent example from monitoring a pile load test in London is presented and the monitoring results are discussed. A complementary finite element analysis with an in-house code is also included which confirms that the monitored data compare quite well with the expected performance of the pile.

It is shown that distributed fibre optic sensing may be used reliably to monitor axially loaded foundation piles. Spatially continuous data about the axial strain from the FO cables can provide profiles of axial force, axial displacement and shaft friction. The latter information can also be used to

develop relevant load-transfer (t - z) curves for further finite element analyses of the foundation piles.

It is therefore suggested that similar monitoring schemes may be used in the future for monitoring axially loaded piles as a standard sensing system. Finally, the wealth of monitoring data may also be used to derive relevant computational models for axially loaded foundation piles.

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ICSECM2017-Paper120

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ICSECM2017-Paper120

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