INNOVATIVE STRUCTURAL HEALTH MONITORING OF REINFORCED CONCRETE PILES USING DISTRIBUTED FIBRE OPTIC SENSING

Loizos Pelecanos[1], Kenichi Soga[2]

1. University of Bath, UK
2. University of California, Berkeley, USA

ABSTRACT. Thousands of piles are built every year in the world and their construction has become an integral part of a building's design and construction. Although so many piles are being built, contractors still find piles that are damaged or their as-built condition is significantly different than the initial design. Pile damage or any compromise in the strength, stiffness or geometry may be detrimental for the structural stability and safety of the superstructure. It is therefore crucial to implement procedures for inspecting and quality-controlling foundation piles, so that their "true" capacity can be reliably estimated. Part of this quality control should be a comprehensive set of reliable detailed instrumentation that can reveal the state of constructed foundation piles.

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 two recent case studies in London were abnormalities in the piles were observed. It is shown that spatially-distributed fibre-optics were able to identify the abnormalities, whereas the point vibrating-wire strain-gauge sensors could not. The monitoring data is also complemented by relevant load-transfer finite-element analysis which was able to confirm that a compromised pile cross-sectional area existed in the pile at several locations.

Keywords: Reinforced Concrete, Resilience, Piles, Structural Health Monitoring, Sensing

Dr Loizos Pelecanos is a Lecturer in Civil Engineering, University of Bath, UK. His research interests include computational mechanics, earthquake engineering, soil-structure interaction, structural health monitoring.
Telephone with Country Code: **+44-1223386250** Email Id: **L.Pelecanos@bath.ac.uk**

Professor Kenichi Soga FICE FREng, Chancellor's Professor, University of California, Berkeley, USA. A world authority in innovative infrastructure sensing and geomechanics.
Telephone with Country Code: **+1-(510) 664-7534**. Email Id: **soga@berkeley.edu**

INTRODUCTION

Reinforced concrete piles are nowadays usually used as the primary foundation type for tall buildings. Instrumented pile load tests are used widely to establish relevant geotechnical parameters for such piles. Traditionally, pile load tests were monitored with a number of discrete point sensors, such as vibrating-wire-strain-gauges (VWSGs). Although these kinds of sensors are accurate and reliable they do not offer continuity of the data. This is due to the discrete values of strain recorded, i.e. only where the VWSG sensor is installed. In cases of complicated soil-structure interaction, a distributed profile along the entire length of the concrete pile is very useful in proiding details of the performance of the pile, such as necking, non-uniform pile diameter, strain localisation etc., perhaps due to concrete anomalies.

Recent developments in optical strain sensing, such as the Brillouin Optical Time-Domain Reflectometry (BOTDR) or Analysis (BOTDA) offer the opportunity to obtain distributed (spatially continuous) values of monitored strain. This paper presents the method of distributed fibre optic sensing and its application in monitoring reinforced concrete piles.

DISTRIBUTED FIBRE OPTIC SENSING

This section provides a brief introduction to 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).

Principle of BOTDR/A

A fibre optic (FO) cable allows light waves from a FO analyser to propagate 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 found to 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 backscattered Brillouin central frequency, v_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, v_α, 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.

Consequently, a measurement of this frequency difference can provide an indication 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.

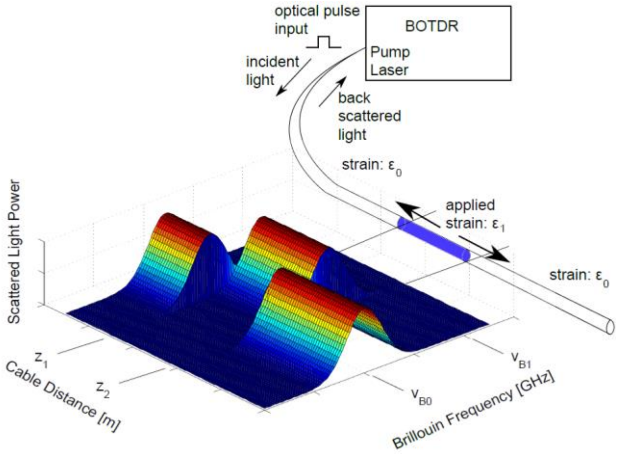


Figure 1 Principle of BOTDR/A.

Fibre Optic cables

Strain on an optical fibre can be generated from two sources, mechanical or thermal. Therefore, in order to distinguish these two sources, two types of optical fibre cables are usually used, which are shown in Figure 2: a Fujikura 4-core single mode fibres reinforced ribbon cable for strain sensing (strain sensing cable) and an 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 are located isolated within a gel which prevents any transfer of mechanical strains from the outer coating. Therefore 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, ε_{mech}.

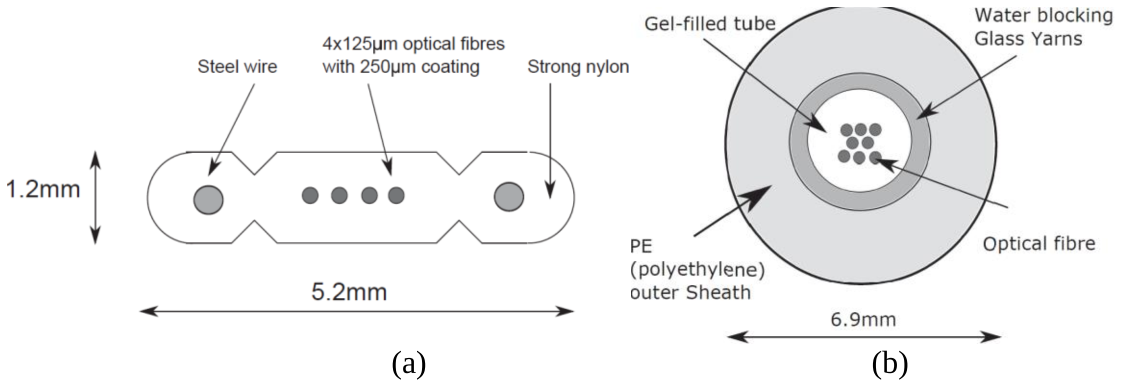


Figure 2 Fibre Optic cables: (a) Fujikura strain cable, (b) Excel Unitube temperature cable.

Sensor installation

Installation of FO cables can be done on site or in a lab in cases of pre-fabricated pile segments. 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 placed in the borehole 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, thus providing a closed loop.

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).

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", Δ_{vbT}, is influenced only by changes in temperature, whereas that from the "strain cable", Δ_{vbS}, is influenced by changes in both mechanical load and temperature.
Therefore, changes in temperature, Δ_T, 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 1.1·10-3 GHz/^{o}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 με/^{o}C).

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

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 5·10-4 GHz/με; and CT is a property of the fibre that determines how the Brillouin frequency is affected by temperature difference, and it is usually around 1.0·10-3 GHz/^{o}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

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

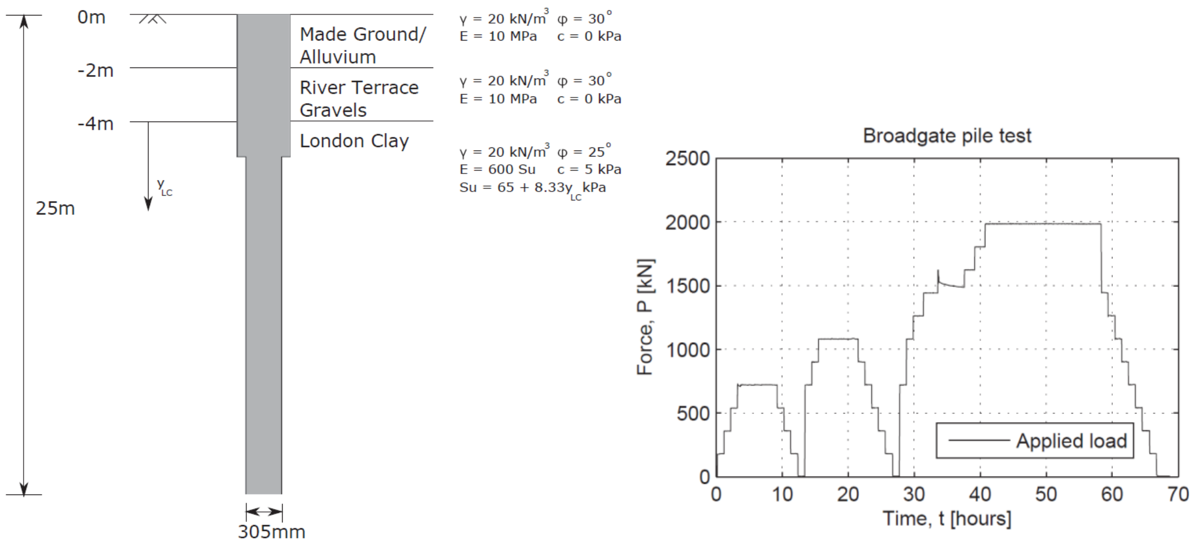
APPLICATION IN REINFORCED CONCRETE PILES

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

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 load 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 VWSGs along the pile depth.



(a) (b)

Figure 3 Pile load test: (a) geometry and soil stratigraphy, (b) applied load time-history.

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=30000MPa. 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 due to the standard resolution of FO being constant and about 30-50με 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.

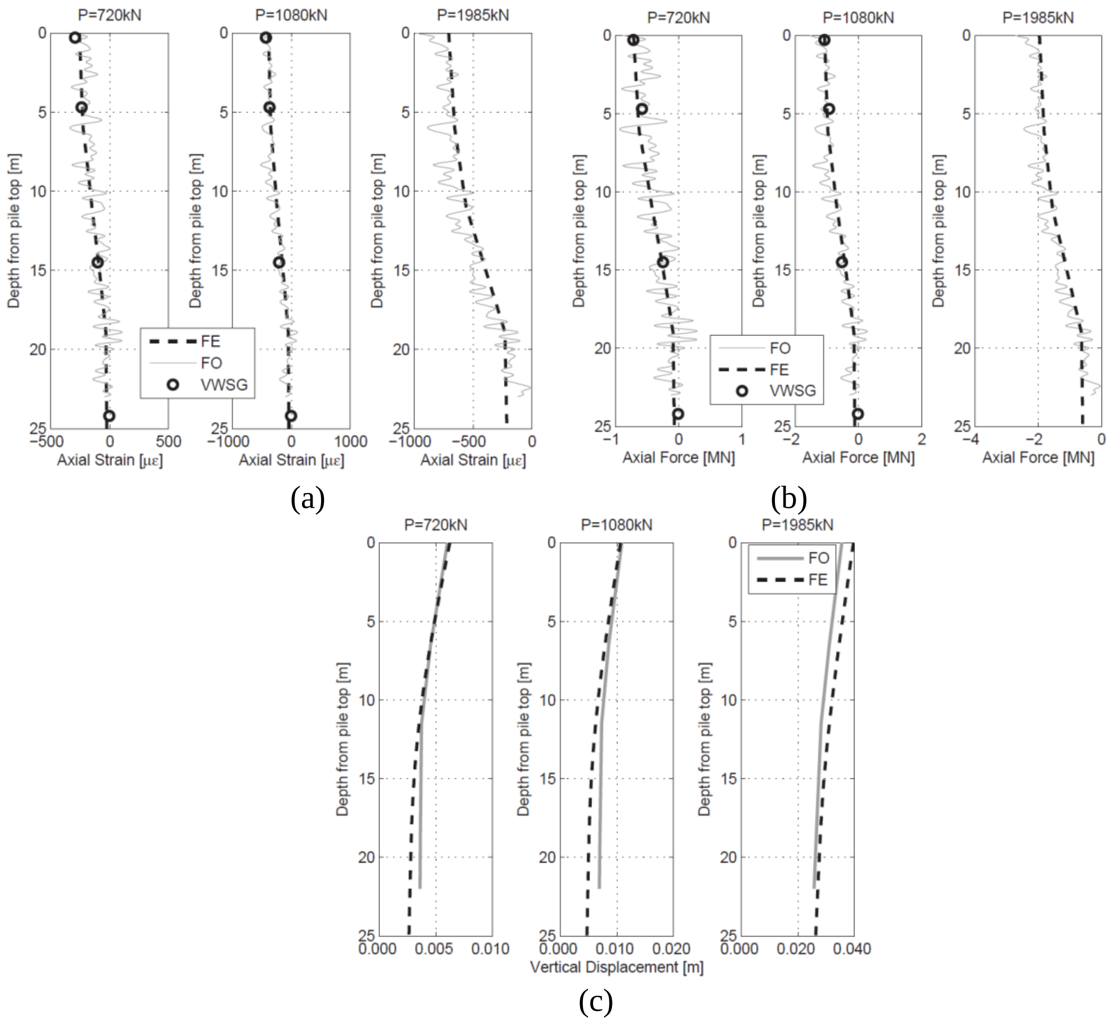


Figure 4 Monitoring data: profiles of (a) axial strain, (b) axial force and (c) vertical displacement.

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 non-linear 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 tm and km 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).

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

All the beam elements and non-linear springs contribute to the global stiffness matrix (which is a sum of the pile stiffness matric, 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, 2019).

$$\left(\left[\mathrm{K_p}\right] + \left[K_s\right]\right) \cdot \{u\} = \{P\} \tag{6}$$

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.

CONCLUDING REMARKS

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 reinforced concrete piles. Reinforced concrete piles can be very conveniently modelled using FO sensing and spatially-continuous strain data can provide information about the strains within the concrete.

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. In the considered study, the monitored strains agree quite well with the numerical predictions.

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 piles.

It is therefore suggested that similar monitoring schemes may be used in the future for monitoring reinforced concrete 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 and provide an insight into the strains developed within the concrete.

ACKNOWLEDGMENTS

This work was initiated at the EPSRC and Innovate UK sponsored Centre for Smart Infrastructure and Construction (CSIC) at the University of Cambridge, when both Authors were working there. Their financial contribution is gratefully acknowledged.

REFERENCES

1. ACIKGOZ M S, PELECANOS L, GIARDINA G, AITKEN J & SOGA K 2017, 'Distributed sensing of a masonry vault during nearby piling', Structural Control and Health Monitoring, vol 24, no 3, p. e1872.
2. ACIKGOZ M S, PELECANOS L, GIARDINA G & SOGA K 2016, 'Field monitoring of piling effects on a nearby masonry vault using distributed sensing.', International Conference of Smart Infrastructure and Construction, ICE Publishing, Cambridge.

3. CHEUNG L, SOGA K, BENNETT P J, KOBAYASHI Y, AMATYA B & WRIGHT P 2010, 'Optical fibre strain measurement for tunnel lining monitoring', Proceedings of the ICE - Geotechnical Engineering, vol 163, no. 3, pp. 119-130.
4. DI MURRO V, PELECANOS L, SOGA K, KECHAVARZI C, MORTON R F & SCIBILE L 2016, 'Distributed fibre optic long-term monitoring of concrete-lined tunnel section TT10 at CERN.', International Conference of Smart Infrastructure and Construction, ICE Publishing, Cambridge.
5. HORIGUCHI T, SHIMIZU K, KURASHIMA T, TATEDA M & KOYAMADA Y 1995, 'Development of a distributed sensing technique using Brillouin scattering', Journal of Light-wave Technology, vol 13, no. 7, pp. 1296-1302.
6. ITEN M 2011, 'Novel applications of distributed fiber-optic sensing in geotechnical engineering', PhD Thesis, ETH, Zurich.
7. KECHAVARZI C, SOGA K, DE BATTISTA N, PELECANOS L, ELSHAFIE M Z E B & MAIR R J 2016, Distributed Fibre Optic Strain Sensing for Monitoring Civil Infrastructure, Thomas Telford, London.
8. KLAR A, BENNETT P J, SOGA K, MAIR R J, TESTER P, FERNIE R, ST JOHN H D & THORP-PETERSON G 2006, 'Distributed strain measurement for pile foundations', Proceedings of the ICE - Geotechnical Engineering, vol 159, no. 3, pp. 135-144.
9. MOHAMAD H 2007, 'Distributed optical fibre strain sensing of geotechnical structures. PhD Thesis', University of Cambridge, Cambridge, UK.
10. OUYANG Y, BROADBENT K, BELL A, PELECANOS L & SOGA K 2015, 'The use of fibre optic instrumentation to monitor the O-Cell load test on a single working pile in London', Proceedings of the XVI European Conference on Soil Mechanics and Geotechnical Engineering, Edinburgh.
11. OUYANG Y, PELECANOS L, SOGA K 2018a, 'Thermo-mechanical response test of a cement grouted column embedded in London Clay', Géotechnique (Under Review).
12. OUYANG Y, PELECANOS L, SOGA K 2018b, ‘Finite element modelling of thermo-mechanical behaviour and thermal soil-structure interaction of a thermo-active cement column buried in London Clay’. 9th European Conference on Numerical Methods in Geotechnical Engineering, Porto, Portugal.
13. OUYANG Y, PELECANOS L, SOGA K. 2018c, ‘The field investigation of tension cracks on a slim cement grouted column’. DFI-EFFC International Conference on Deep Foundations and Ground Improvement: Urbanization and Infrastructure Development-Future Challenges, Rome, Italy.
14. PELECANOS L, SOGA K, HARDY S, BLAIR A & CARTER K 2016, 'Distributed fibre optic monitoring of tension piles under a basement excavation at the V&A museum in London.', International Conference of Smart Infrastructure and Construction, ICE Publishing, Cambridge.
15. PELECANOS L, SOGA K, CHUNGE M P M, OUYANG Y, KWAN V, KECHAVARZI C & NICHOLSON D 2017a, 'Distributed fibre-optic monitoring of an Osterberg-cell pile test in London.', Geotechnique Letters, vol 7, no. 2, pp. 1-9.
16. PELECANOS L, SOGA K, ELSHAFIE M, DE BATTISTA N, KECHAVARZI C, GUE, C Y, OUYANG Y AND SEO H., 2017b. Distributed Fibre Optic Sensing of Axially

Loaded Bored Piles. Journal of Geotechnical and Geoenvironmental Engineering. (In Press).

17. PELECANOS L, SOGA K. 2017a, Innovative structural health monitoring of foundation piles using distributed fibre-optic sensing. 8th International Conference on Structural Engineering and Construction Management, Kandy, Sri Lanka.
18. PELECANOS L, SOGA K 2017b, ‘The use of distributed fibre-optic strain data to develop finite element models for foundation piles’. 6th International Forum on Opto-electronic Sensor-based Monitoring in Geoengineering. Nanjing, China, November, 2017.
19. PELECANOS L, SOGA K. 2018, ‘Development of load-transfer curves for axially-loaded piles based on inverse analysis of fibre-optic strain data using finite element analysis and optimisation’. 9th European Conference on Numerical Methods in Geotechnical Engineering Porto, Portugal.
20. PELECANOS L & SOGA K 2019, 'Using distributed strain data to evaluate load-transfer curves for axially loaded piles', Journal of Geotechnical & Geoenvironmental Engineering, ASCE (Under Review).
21. SCHWAMB T, SOGA K, MAIR, R J, ELSHAFIE M Z E B, R S, BOQUET C & GREENWOOD J 2014, 'Fibre optic monitoring of a deep circular excavation', Proceedings of the ICE - Geotechnical Engineering, vol 167, no. 2, pp. 144-154.
22. SOGA K 2014, 'XII Croce Lecture: Understanding the real performance of geotechnical structures using an innovative fibre optic distributed strain measurement technology', Rivista Italiana di Geotechnica, vol 4, pp. 7-48.
23. SOGA K, KECHAVARZI C, PELECANOS L, DE BATTISTA N, WILLIAMSON M, GUE C Y, DI MURRO V & ELSHAFIE M 2017, 'Distributed fibre optic strain sensing for monitoring underground structures - Tunnels Case Studies ', in S Pamukcu, L Cheng (eds.), Underground Sensing, 1st edn, Elsevier.
24. SOGA K, KWAN V, PELECANOS L, RUI Y, SCHWAMB T, SEO H & WILCOCK M 2015, 'The role of distributed sensing in understanding the engineering performance of geotechnical structures', Proceedings of the XVI European Conference on Soil Mechanics and Geotechnical Engineering, Edinburgh.