Institution:
University of Cambridge

Unit of Assessment:
UoA15

Title of case study:
Distributed Fibre Optic Sensing for Civil Engineering Infrastructure

1. Summary of the impact (indicative maximum 100 words)

Research at the University of Cambridge Department of Engineering (DoEng) has led to the creation of a method for measuring strain throughout a range of civil engineering structures using Distributed Fibre Optic Sensing (DFOS) and computing the stresses in these structures. This detailed information and associated insights have reduced reliance on conservative safety margins, while giving greater assurance of safety. The result has been significant reductions in construction materials and construction time. The work has generated direct savings of over GBP15M in three major infrastructure projects from 2011 to 2013 including Crossrail. It has had a wider influence across the whole industry by setting standards for geothermal piles in 2012, which were instrumental in the creation of this new industrial sector, and by changing attitudes in construction about the value of instrumentation and modelling.

2. Underpinning research (indicative maximum 500 words)

Professor Robert Mair (appointed as Professor in the DoEng in 1998), Professor Kenichi Soga (appointed as Lecturer in the DoEng in 1994 and promoted to Professor in 2007) and Dr Mohammed Elshafie (appointed Lecturer in the DoEng in 2011) have been the Principal Investigators for the research in the DoEng.

Mair and Soga realised that the accurate measurement of strain throughout a civil engineering structure, coupled with geotechnical and structural modelling, is essential to understand its performance, gain new insights into fundamental soil structure interactions and optimise design. They saw the potential for Distributed Fibre Optic Sensing (DFOS), in particular Brillouin Optical Time Domain Reflectometry (BOTDR), to measure strain in structures during construction and throughout its lifetime. They secured approximately GBP500K in a grant application to the Cambridge MIT Institute to research methods for deployment, data gathering and analysis for a project that ran from 2002 to 2005. This exploratory project included successful trials on the Channel Tunnel Rail Link (HS1) and a series of research projects followed:

- Smart Foundations with Distributed Fibre Optics Technology (EPSRC, GBP281K, 2006-2009)
- Commercialisation of Smart Foundation System (EPSRC, GBP88K, 2010-2011)
- Crossrail Knowledge Transfer Partnership and follow on (TSB/KTP and Crossrail, GBP764K, 2010-2012)
- Innovation Knowledge Centre for Smart Infrastructure and Construction (EPSRC, GBP9.5M, 2011-2016).

The research was informed and tested by a series of consulting projects from 2011 to 2013 with Southend-on-Sea Borough Council, Thames Water, Crossrail, Skanska, Magpie Environmental Drilling Services, Vlaamse Overheid, Wentworth House Partnership, National Grid, Virginia Tech (USA), Myriad CEG and Arup involving a wide variety of structures including piles, pipelines, tunnels, slopes, soil nails, motorway embankments and cuttings (GBP391K).

The key research result was a robust and innovative DFOS optical fibre installation technique for piles, retaining walls and tunnels which was used and refined in a series of case studies, providing important new insights into detailed microstrain soil-structure interaction mechanisms in large, complex civil engineering structures. Specific findings were as follows:

a) A new understanding of mechanical and thermal behaviour of piles: theoretical analysis comparing measurements from traditional localised strain devices and DFOS for a vertically loaded pile in layered soil [1]; the DFOS method has also elucidated fundamental behaviour of thermal energy piles, proving that their load-bearing capacity is not compromised by thermal cycles [2].

b) A new data processing and temperature compensation method was produced to calculate strains and ultimately deformation of retaining walls. This was based on detailed measurement of axial and lateral deformation of a secant pile retaining wall using the Cambridge DFOS system [3].

c) A completely new understanding of the effect of ageing and changing ground conditions on joint movements in concrete lined London Underground tunnels was obtained from use of DFOS [4]. The system was also used to assess the performance of a Victorian masonry tunnel affected by the construction of a new tunnel beneath it, avoiding the need for extremely costly internal bracing [5]. The DoEng team applied the same system in Singapore to measure circumferential strains in real time induced by excavating an adjacent tunnel in close proximity. It also provided enhanced understanding of lining deformation mechanisms, which is essential for improving future designs of twin tunnel-soil interactions [6]. The DoEng DFOS research applied to tunnels has proved that the system can reliably measure and elucidate the behaviour of a variety of tunnel types and showed the advantages of DFOS in accurately measuring continuous strain profiles and in its geometric adaptability.

3. References to the research (indicative maximum of six references)

1. *Klar, A., Bennett, P.J., Soga, K., Mair, R.J., Tester, P., Fernie, R., St John, H.G. and Torp-Peterson, G. (2006): “Distributed strain measurement for pile foundations,” *Proceedings of the ICE- Geotechnical Engineering,* Vol. 159, No. GE3, pp.135-144 (awarded the Crampton Prize of the Institution of Civil Engineers). DOI: 10.1680/geng.2006.159.3.135

2. *Bourne-Webb, P.J., Amatya, B., Soga, K., Amis, T., Davidson, C. and Payne, P. (2009): “Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspects of pile response to heat cycles,” *Géotechnique,* Vol. 59, No. 3, pp. 237–248. DOI: 10.1680/geot.2009.59.3.237

3. Mohamad, H., Soga, K. and Pellow, A. (2011): “Performance monitoring of a secant piled wall using distributed fibre optic strain sensing,” *Journal of Geotechnical and Geoenvironmental Engineering,* Vol. 137, No. 12, pp. 1236-1243. DOI: 10.1061/(ASCE)GT.1943-5606.0000543

4. Cheung, L.L.K., Soga, K., Bennett, P.J., Kobayashi,Y., Amatya, B. and Wright, P. (2010): “Optical fibre strain measurement for tunnel lining monitoring” *Proceedings of the ICE, Geotechnical Engineering*, Vol. 163, No. GE3, pp. 119–130. DOI: 10.1680/geng.2010.163.3.119

5. *Mohamad, H., Bennett, P.J., Soga, K. Mair, R.J. and Bowers, K. (2010): “Behaviour of an old masonry tunnel due to tunnelling-induced ground settlement,” *Géotechnique,* Vol. 60, No. 12, pp. 927 –938. DOI: 10.1680/geot.8.P.074

6. Mohamad, H., Soga, K., Bennett, P.J., Mair, R.J. and Lim, C.S. (2012): “Monitoring twin tunnel interactions using distributed optical fiber strain measurements” *Journal of Geotechnical and Geoenvironmental Engineering,* American Society of Civil Engineers, Vol. 138, No. 8, pp. 957-967. DOI: 10.1061/(ASCE)GT.1943-5606.0000656

*Best represent the quality of the underpinning research

4. Details of the impact (indicative maximum 750 words)

This research has been applied to over 20 infrastructure projects. Examples of impact on these projects are presented below.

<u>Skanska Bevis Marks foundation pile reuse monitoring (2011, Soga and Elshafie)</u>

When a structure is demolished and another built on the same site, it is normally impossible to reuse the existing foundation piles, because their condition is unknown. Skanska sought to reuse foundations on Bevis Marks building and asked the DoEng if its research could be applied to determine the condition of the old piles. Soga and Elshafie used underpinning research finding (a) to instrument the piles by coring into them from top to bottom to insert DFOS cables. This enabled the DoEng team to measure the evolution of strain during demolition of the existing structure and throughout construction of the new building. This monitoring produced key evidence proving that the existing piles were able to take the loads. The total cost saving on the project was GBP6M, because it would have cost GBP5M to remove the 67 old piles and associated walls/slabs plus GBP1M to install replacement piles. Less material was used in construction, which equates to a saving of 1000 tonnes of CO_2, which would otherwise have been released during the course of construction. In addition, 3-6 months of construction programme time were saved on the project. The project won the Ground Engineering Sustainability Award 2013 for Skanska [7]. The EPSRC website, Growth Stories, states: *"In the future, Skanska plan to use the same approach. By reusing foundations the construction programme can be shortened, typically saving GBP2-3M per project plus associated CO_2 and time savings."*

<u>Thermal energy piles – developing an industry standard (2012, Soga)</u>
Underpinning research finding (a) was fundamental to the creation of the Ground Source Heat Pump Association (GSHPA) "Thermal Pile Design, Installation & Materials Standards", Issue 1.0, published by the GSHPA on 1 October 2012. Soga was the co-author of these standards. Chair of the GSHPA and Geotechnics Director at Arup [9], states: *"This work has generated a completely new industry sector for Geothermal Pile specialists"*.

<u>Thames Water – Thames Tideway project (2011 – present, Elshafie, Mair and Soga)</u>
When constructing a shaft next to a building, owners of the building need assurance that damage will not result from ground movements. Often, the only way to provide assurance is to employ excessive protective measures, which increase project costs and introduce delays. Thames Water asked Elshafie, Mair and Soga to use underpinning research finding (b) to apply a performance-based design approach to justify a reduced level of protection on their next major Thames Tideway tunnel and shaft excavation project, comprising 25km of 7m diameter tunnel and 20 major shafts (total cost GBP4B). Thames Water has estimated that this will save at least GBP10M on the cost of construction and has enabled innovation in design through improved understanding of the structural behaviour and improved understanding and confidence in the fundamental behaviour of the shafts and the associated ground movements. Senior Technical Consultant on the Thames Tideway project from Thames Water [10], said in 2013: *"Perhaps, more importantly, the confirmation of the design models that will be realised by this work will give greater confidence and less objection by third party structure owners and operators thus reducing level of institutional objection during Planning process."* Thames Water's approach has been changed by this successful result; it will apply the method to all future major shaft excavations.

<u>Tubelines/London Underground (2010, Soga)</u>
Based on research finding (c) Soga was invited to install DFOS in a concrete segmental lining section of the Jubilee Line tunnel between Bond Street and Baker Street station with the aim of using the information on the observed movements of segmental joints to determine the mechanisms of deformation and whether the whole lining section needed to be replaced or whether it would be sufficient to reinforce the lining with steel straps at much lower cost. The measurements and subsequent analysis showed that it was appropriate to continue with reinforcement with steel straps as a safe temporary option, rather than having to immediately replace the tunnel lining. This example shows the value of DFOS in guiding infrastructure owners on the right course of action both in terms of safety and long-term maintenance. It is difficult to put monetary value on this but making safety-critical maintenance decisions to avoid expensive disasters has considerable value. Profession Head, Deep Tube Tunnels, London Underground [11] said in 2013: *"The data gained from this and other monitoring systems was invaluable in proving that the tunnel would continue to distort and deteriorate if untreated. This led to the important decision to temporarily reinforce and subsequently completely rebuild the affected section of tunnel".*

<u>Overall Impact:</u>
Associate Director and Lead Geotechnical Engineer, Arup [12], stated in 2013: *"The Fibre Optics work at Cambridge has set a new agenda for monitoring strains and temperature in a number of civil engineering structures", "Companies across the world are using the outcomes of the research"*

and "The research has been instrumental in developing new standards for understanding diaphragm wall shaft deformation behaviour and response of piles to thermal loading".

CEO of Crossrail [13], stated in 2013, *"[Robert Mair's] team's work on Crossrail and other related projects is cutting edge. Optic fibre strain gauges to measure the performance of our tunnel sections and shafts - something that is a first anywhere in the world. Developing asset management systems that detect changes in the condition of the asset over its life cycle. Both these projects are being developed for us to understand better how our structures and assets behave and how long term, we can save money through more economic design and reduced life cycle costs."*

Consultancy income for DoEng (Soga, Mair and Elshafie)
The research has led to the DoEng team being commissioned as consultants on a number of construction projects, using the underpinning research findings to determine the most cost effective solutions during construction projects. The DoEng has earned GBP391K across 21 projects since May 2008.

Industry engagement in the Centre for Smart Infrastructure and Construction (2011 – present, Mair, Soga and Elshafie)
In 2011, the DoEng team was awarded a GBP9.5M grant from EPSRC and Technology Strategy Board to develop the Centre for Smart Infrastructure and Construction (CSIC). CSIC has attracted an additional GBP7M from industry (both cash and in kind) to continue to develop and demonstrate smart infrastructure solutions including DFOS. One of the major activities of CSIC is to develop robust methods and equipment for DFOS deployment so that industry can lead in the deployment of DFOS monitoring systems. Industry partners are strongly supporting this activity by continuing to invite the DoEng to deploy DFOS to inform their construction projects, and companies such as Costain, Skanska and Laing O'Rourke are actively discussing how they can develop their own capabilities. Based on this, CSIC is developing training for construction operatives and engineers in deployment of DFOS. CSIC has 40 industry partners including Costain, Laing O'Rourke, Skanska, Arup, Atkins, Halcrow, Mott MacDonald, WSP, Parsons Brinkerhoff, Crossrail, Network Rail, London Underground, Thames Water and Transport for London [14].

5. Sources to corroborate the impact (indicative maximum of 10 references)

7. Ground Engineering Awards: http://www.geawards.com/670564
8. "Sensors pave the way to recycle buildings", Growth Stories, EPSRC website, http://www.epsrc.ac.uk/growth/d_index.php#construction~sensors-pave-the-way-to-recycle-buildings
9. Statement received from Chair of the GSHPA and Geotechnics Director at Arup
10. Statement received from Senior Technical Consultant, Thames Tideway Tunnel project, Thames Water
11. Statement received from Profession Head, Deep Tube Tunnels, London Underground
12. Statement received from Associate Director and Lead Geotechnical Engineer, Arup
13. Statement received from CEO, Crossrail
14. CSIC website: http://www-smartinfrastructure.eng.cam.ac.uk/partners/industry.html