Institution: University of Cambridge		
Unit of Assessment: UoA12 Engineering		
Title of case study: Smart Infrastructure		
Period when the underpinning research was undertaken: 2002 to 2018		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof Robert Mair	Professor of Civil Engineering Director of Research	1998 – 2017 2017 – present
Prof Ashwin Seshia	Professor of Microsystems Technology	2002 – present
Prof Kenichi Soga	Professor of Civil Engineering	1994 – 2016
Dr Matt DeJong	Senior Lecturer in Structural Engineering	2009 – 2018
Period when the claimed impact occurred: August 2013 to July 2020		
Is this case study continued from a case study submitted in 2014? No		

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

Research at the University of Cambridge into sensing and data analytic technologies has led to new approaches to the performance and safety monitoring of infrastructure assets during both construction and operation. Examples of impact include:

- major construction costs savings, improved safety on construction sites, and the protection of historic buildings during underground construction. The new monitoring techniques have led to one business alone reducing CO_2 emissions by 1,000 tonnes since 2016 through reduced use of construction materials
- Over 25 new jobs, through the creation of three spin-out companies and Skanska's CemOptics new instrumentation system based on the research
- Addition of fibre optic sensing technology to the Institution of Civil Engineers guidelines on practice

2. **Underpinning research** (indicative maximum 500 words)

The development and maintenance of civil engineering infrastructure involves major investments by government and the private sector. Despite the high asset value and the critical economic and social importance of reliable and safe infrastructure, technical asset management approaches are historically low-technology and low fidelity, relying on site visits and physical testing at a very limited number of points (in space and time). It was recognised by researchers at the Department of Engineering at the University of Cambridge that developing new sensor technologies and data analytic approaches could transform infrastructure construction and whole-life management of assets, increasing safety during construction whilst achieving economies through performance-based design, reducing construction delays, supporting cheaper and less disruptive maintenance of operating infrastructure, and extending the lifetime of high-value infrastructure assets.

Research at the Department developed new distributed fibre optic Sensing (DFOS) [R1] and Fibre Bragg Grating (FBG) [R2] methods and techniques for measuring strain and temperature to infer movement and cracking for various construction types. The technologies provide unprecedented spatial and temporal resolution, enabling more efficient and less interrupted construction, and improved serviceability of built assets with continuous monitoring. The research team collected strain data which was synthesised with geotechnical and structural modelling to understand the engineering performance of complex structures. The research, undertaken in 2002–2008, trialled the technologies on a series of field-scale deployments and carried out a number of successful trials, such as on the Channel Tunnel Rail Link (HS1) [R3].

A key research outcome was a robust optical fibre sensor installation technique for piles, retaining walls and tunnels that could provide new insights into detailed soil-structure interaction mechanisms for large, complex engineering structures. Specific research developments included:

- A new understanding of the mechanical and thermal behaviour of piles using DFOS data [R1].
- A new data processing and temperature compensation method for calculating strains and ultimately deformation of retaining walls based on detailed measurement of axial and lateral deformation of a piled retaining wall using the DFOS system [R4].

The research was further developed through a series of projects from 2008 to 2013 with Southend-on-Sea Borough Council, Thames Water, Crossrail, Skanska, Vlaamse Overheid (Belgium), Wentworth House Partnership, National Grid, Virginia Tech (USA), Highways England, Myriad CEG and Arup for a wide variety of structures including piles, pipelines, tunnels, slopes, soil nails, motorway embankments and cuttings.

Monitoring and sensing techniques were explored in the context of ageing and historic infrastructure. New insights into the flexible behaviour of a Victorian masonry arch tunnel, affected by the construction of a new tunnel located directly below, were obtained using DFOS, avoiding the potential need for costly remedial measures [R3]. The research team applied the same system in Singapore to measure circumferential strain in real time induced by excavating an adjacent twin tunnel. It provided enhanced understanding of lining deformation mechanisms, which is essential for improving future designs of twin tunnel-soil interactions [R5]. The research demonstrated that the DFOS system could reliably measure strain profiles for a variety of tunnel types. The sensing technologies were extended to other structures, including masonry arches [R2], and bridges. Supported by data analysis techniques, the sensing technologies were applied to evaluate in-service performance of structures and the effectiveness of maintenance measures, which is critical to improving the existing assessment techniques for masonry viaducts and other heritage sites.

To support maintenance-free wireless monitoring of infrastructure assets, research also showed that sufficient energy can be harvested from ambient vibration [R6] to power sensors and sensor systems under a range of monitoring scenarios. The research included a demonstration of the first self-powered wireless sensors on the Forth Road Bridge.

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

R1. 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). DOI: 10.1680/geng.2006.159.3.135

R2. **Acikgoz, S., DeJong, M., Kechavarzi, C., Soga, K**. (2018) Dynamic response of a damaged masonry rail viaduct: Measurement and interpretation. *Engineering Structures*. Vol.168, pp.554-558. DOI: 10.1016/j.engstruct.2018.04.054

R3. 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

R4. 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

R5. 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

R6. Jia, Y., Yan, J., **Soga, K.** and **Seshia A. A.** (2014) A parametrically excited vibration energy harvester, *Journal of Intelligent Material Systems and Structures* 25(3):278-289, https://doi.org/10.1177/1045389X13491637.

Research is published in peer-review journals. Research was supported by competitively won grants.

Grants:

(a) EPSRC EP/I019308/1 Innovation Knowledge Centre for Smart Infrastructure and Construction (2011 to 2016). GBP4,956,319; (b) EPSRC EP/K000314/1 Innovation and Knowledge Centre for Smart Infrastructure and Construction - Collaborative Programme Tranche 1 (2012 to 2016). GBP2,311,585;(c) EPSRC EP/L010917/1 IKC Tranche 2 (2013 to 2017). GBP2,184,284; (d) EPSRC EP/D040000/1 Smart Foundations with Distributed Fibre Optics Technology (2006 to 2009). GBP281,307; (e) EPSRC EP/H007423/1 Commercialisation of Smart Foundation System (2011). GBP88,000; (f) EPSRC EP/D076870/1 Smart Infrastructure: Wireless sensor network for condition assessment and monitoring of infrastructure (2006 to 2010). GBP777,034; (g) InnovateUK Crossrail Knowledge Transfer Partnership (2010 to 2012). GBP764,000.

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

The research on infrastructure sensing has led to the development and deployment of smart infrastructure approaches for asset monitoring and management. Leading businesses in infrastructure construction and management have deployed technologies developed in the research, with knowledge transfer supported by the creation of the Cambridge Centre for Smart Infrastructure and Construction (CSIC) at the Department of Engineering in 2011. CSIC is a UK Innovation and Knowledge Centre funded by Innovate UK, EPSRC and 28 industry partners. CSIC partners in 2020 include CERN, Crossrail, EDF Energy, Highways England, Arup, Costain and Laing O'Rourke. The research has delivered major construction cost savings, improved safety on construction sites, and protected historic buildings during underground construction. It has also impacted technical construction specifications and has led to the creation of three spin-out companies and new jobs. CSIC has identified that smart infrastructure is a global opportunity worth somewhere between GBP2,000,000,000,000 and GBP4,800,000,000,000 [E8].

Infrastructure industry practices

The smart sensing research led to fibre optic sensing technology being added to the 2016 Institution of Civil Engineers (ICE) *Specification for Piling and Embedded Retaining Walls* [E1] and an ICE Guide on infrastructure sensing, developed by CSIC, which was published by the ICE in 2017 [E2]. In the ICE Guidance Paper, Sir John Armitt, ICE Past-President, summarised the impact of smart infrastructure sensing:

"*Infrastructure sensing is becoming simpler, cheaper and more versatile. Data can now be readily collected, analysed in real time and compared across assets, companies and countries... This enables better decisions on the construction of future assets, better running of today's existing assets, and far better avoidance of failure, not to mention long term financial benefits such as significantly reducing whole-life costs.*"

ICE Past-President [E2]

CSIC hosts the International Conference on Smart Infrastructure and Construction, held every three years. The 2019 conference was attended by over 200 delegates from over 50 companies and 35 countries [E3].

Skanska: integrity testing and quality control of buried structures

Following a CSIC demonstration project in 2014, Cementation Skanska Ltd developed an instrumentation system with CSIC and Arup to monitor piled foundations and other subsurface constructions based on the research in [R1, R4]. The system has been patented and commercialised and branded as CemOptics. The CemOptics system was used in over 12 projects between 2014 and 2019 in the UK and abroad, including in the GBP1,000,000,000 Northern Line extension. Since initial deployment in 2014, over 100km of fibre optics has been installed, completely replacing the existing, riskier to install and more cumbersome to connect point sensing methods.[E4] Benefits include reduced remedial work and associated costs, reduced use of materials, elimination of site accidents and injuries,

improved productivity, and reduced CO_2 emission of 1,000 tonnes through a reduction in construction materials [E4]. Skanska created a new business team around the CemOptics technology, with six members of staff and turnover exceeding GBP500,000 in 2019 [E4].
"*The use of distributed fibre optic sensing, and the processes which were developed through CSL's [Skanska] collaboration with CSIC, have become business as usual on our ground engineering projects. The data which we are able to collect provides new insights into geotechnical performance and is becoming an invaluable tool in the verification and quality assurance of our products*."

Testing and Monitoring Manager, Cementation Skanska [E4]

London Underground: protection of heritage sites during tunnel construction
CSIC real-time smart sensing technologies were installed in 2017 in the Grade I listed St Mary's Abchurch and Mansion House buildings to monitor deformation of the heritage sites during the construction of tunnels for the Bank Station upgrade. The monitoring technologies led to savings of over GBP1,000,000 by avoiding traditional mitigation measures, including compensation grouting and temporary propping [E5]. The project won the 2018 New Civil Engineer Tunnelling "Innovation in Instrumentation and Monitoring Award" and the 2018 New Civil Engineer "Research Impact: Application in the industry" award [E6].

Network Rail: asset management

Network Rail (NR) has used the developed sensing technologies since 2016 on new and historic bridges and viaducts. Two new bridges on the West Coast Main Line near Crewe, constructed as part of GBP250,000,000 Stafford Area Improvements Programme, were instrumented in 2017 with CSIC monitoring technologies [E5]. In 2017 a monitoring system was fitted to a Victorian viaduct in Leeds [E5, R6]. The sensing and associated data analysis tools have enabled better targeted maintenance, identification of future maintenance needs and improved safety. CSIC sensing technologies were also fitted by AECOM in 2016-17 to a 150-year old skewed masonry arch bridge in North Yorkshire [E7] to reduce road closures required with standard measuring approaches. Network Rail plans to invest GBP190,000,000 between 2019 and 2024 in asset monitoring technologies and data analysis, which is estimated to generate gross benefits of GBP270,000,000 over the next 10 years [E8].

"*We continue to work closely with the Cambridge CSIC team on a number of projects, using fibre optic monitoring technology. This promises to revolutionise our asset management approach and practices*".

Head of Geotechnics, Network Rail [E9]

Spin-off companies
The smart infrastructure sensing research at the Department has also led to the creation of three spin-off companies:

- UtterBerry Ltd (incorporated in 2013) supplies wireless sensing technology and equipment and currently employs eight people [E10].
- 8power Limited (incorporated in 2015) has created 10 jobs, attracted investment of GBP3,600,000 [E11] and won the Cambridge Graduate Business of the Year (2017) in the Business Weekly Awards 2017. 8power is commercialising self-powered wireless sensors, and has been working with Severn Trent and Anglian Water.
- Epsimon Ltd (incorporated in 2016) provides consultancy on smart instrumentation and monitoring. [Text removed for publication] [E12].

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

E1. ICE Specification for Piling and Embedded Retaining Wall, Third edition (2016), Institution of Civil Engineers (p154-158 and p181-191).
E2. Guidance Paper, Intelligent Assets for Tomorrow's Infrastructure: Guiding Principles, Institution of Civil Engineers (2017) (p. 3).

E3. List of attending organisations at the 2019 International Conference on Smart Infrastructure and Construction.

E4. Case study with Cementation Skanska. Approval of the case study text by the Chief Engineer and Testing and Monitoring Manager.

E5. CSIC 2018 Annual Review (pp.14-15, p.16, p.17)

E6. New Civil Engineer Tunnelling 2018 “Innovation in Instrumentation and Monitoring Award”. New Civil Engineer 2018 “Research Impact: Application in the industry” award.

E7. CSIC 2019 Annual Review. Skewed masonry arch bridge case study by AECOM and CSIC (p.30).

E8. National Infrastructure Commission report (2017) (p.23).

E9. Correspondence with Head of Geotechnics, Network Rail, 19/07/19

E10. LinkedIn profile of UtterBerry

E11. Email correspondence with the CEO, 8power.

E12. Email correspondence with the Director, Epsimon.