# CSIC

Cambridge Centre for
**Smart Infrastructure and Construction**

## ANNUAL REVIEW 2015

# DELIVERING IMPACT

**sensors**

**assets**

**cities**

UNIVERSITY OF CAMBRIDGE

# IMPACT

***noun:*** **a marked effect or influence**

***verb:*** **have a strong effect on someone or something**


*CSIC deployment team installing fibre optic temperature and strain cables on a pile at the Victoria and Albert Museum, London*

## Contents



# Transforming the future of infrastructure through smarter information

## Steering Group

Professor John Burland CBE, Imperial College (Chair)
Dr Keith Bowers, London Underground
Alan Couzens, Infrastructure UK
Tim Embley, Costain
Rab Fernie, formerly Technical Director, Cementation Skanska
Tom Foulkes, Victoria BID
Steve Hornsby, Independent Consultant
Professor Robert Mair CBE, CSIC, University of Cambridge
Professor Duncan McFarlane, CSIC, University of Cambridge
Professor Andrew McNaughton, HS2
Professor Campbell Middleton, CSIC, University of Cambridge
Richard Ploszek, Royal Academy of Engineering & Infrastructure UK
Dr Jennifer Schooling, CSIC Director
Professor Kenichi Soga, CSIC, University of Cambridge
Dr Scott Steedman CBE, British Standards Institute (BSI)
John St Leger, Strainstall UK Ltd
Paul Westbury CBE, Laing O'Rourke
Professor Ian White, Department of Engineering, University of Cambridge

## International Advisory Group

Professor Tom O'Rourke (Chair), Cornell University, USA
Professor Yozo Fujino, University of Tokyo, Japan
Professor Bill Spencer, University of Illinois, USA
Professor Paul Wright, University of California, Berkeley, USA
Professor Hehua Zhu,Tongji University, China

Cover photograph by Peter Knott, CSIC: Instrumentation of a pile at the Newfoundland Tower site at Canary Wharf, London

**20**
**Awards and Shortlistings**

**41**
**Industry Partners**

**636**
**Publications and Citations**

**389**
**Trained by CSIC**

**81**
**Site Demonstrations**

**£954,154**
**Commercial Income**

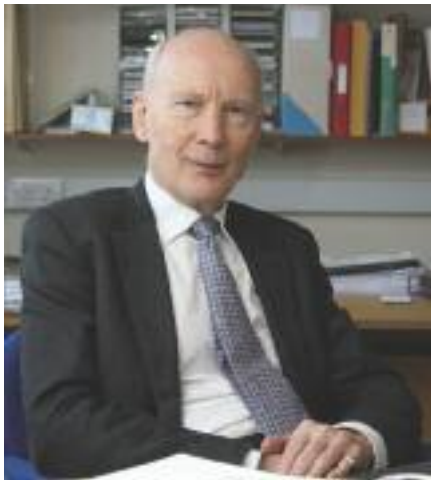
**£13.8M**
**Non-IKC Research Grant Funding**

Cumulative figures from 2012 to March 2015

# INTELLIGENT INFRASTRUCTURE: BUILDING A BETTER FUTURE

*"The Institution of Civil Engineers (ICE)* State of the Nation 2014 *report emphasises how vital infrastructure is to our society – our quality of life depends on it functioning effectively and our reliance on it becomes painfully evident when infrastructure systems fail"*

*CSIC team working through the night instrumenting beams for Staffordshire Alliance railway bridges at the Laing O'Rourke Explore Manufacturing facility*



**Professor Robert Mair**
**Head of CSIC**
**Head of Civil Engineering**
**University of Cambridge**
**Vice President, ICE**

The key aim of the Centre for Smart Infrastructure and Construction (CSIC) is that emerging technologies from world-leading research at the University of Cambridge will transform the construction industry through a whole-life approach to achieving sustainability in construction and infrastructure in an integrated way.

These emerging technologies include fibre optics, wireless sensor networks, energy harvesting, micro electro mechanical systems (MEMS) and computer vision. Crucial elements of these technologies are the innovative application of the latest sensor technologies and data management tools to the construction industry, both during infrastructure construction and throughout its design life. As an Innovation and Knowledge Centre (IKC), the key objective of CSIC is to integrate these innovations for knowledge transfer and exploitation by industry.

The impact of CSIC's activities and the application of its tools and technologies will be major transformations in the approaches to the design, construction and use of complex infrastructure – leading to step changes in:

- improved health and productivity
- greater efficiency in design and performance
- a low-carbon society
- sustainable urban planning and management

To secure these transformations the construction and infrastructure industry must advance economically and sustainably.

By working with our Industry Partners, CSIC develops, deploys and delivers the tools and technologies that bring this opportunity. The aim is to deliver value to industry by:

- improving margins
- reducing costs
- enhancing returns
- extending productive life of assets

There will be very substantial UK and international markets for exploitation of these new technologies by the construction industry – particularly for contractors, specialist instrumentation companies and owners of infrastructure.

CSIC's aims acknowledge the essential place infrastructure has in society. The UK Government's *National Infrastructure Plan 2014* highlights the strong economic case for infrastructure investment:

- it emphasises the need for successful delivery – projects delivered faster, better and more cost-effectively
- it highlights as a key priority the necessity to develop best practice to inform industry how infrastructure projects should be managed and run
- it stresses the need for improved asset management and whole-life principles – central to CSIC's objectives

CSIC aims to transform the future of infrastructure through smarter information. This is fully aligned to the Government's *Construction 2025* report published in 2013 highlighting the importance of building the UK's competitive advantage by investing in smart construction and digital design. The report emphasises:

- how new technologies and digital techniques have already made a huge impact in other industries
- how in the coming years these technologies will drive a step change in how we build and how our built environment will be operated
- how crucial it is that the emergence of new technologies in sensors and data management become embedded in our assets, enabling performance to be constantly monitored, driving substantial efficiency gains in facilities and asset management. This will provide owners with a full understanding of the performance of their assets, both during construction and throughout their design life – a fundamental aim of CSIC

CSIC is putting into practice a number of key actions recommended by ICE's *State of the Nation 2014* report which will improve and enhance performance, and ensure that our infrastructure is resilient when faced with the many challenges ahead – from climate change to population growth. Recommended actions include the following:

- commitment to a regime of planned, preventative maintenance. This key objective is underpinned by CSIC's sensing and data analysis models that provide impact by enabling smarter, proactive asset decision-making for industry
- engineering professionals should simplify and speed up the standards change process. CSIC is collaborating with BSI and producing best-practice guides (to be published by the ICE) for immediate use by industry on recent innovations affecting new industry standards: fibre optic strain sensing; wireless sensor networks for infrastructure monitoring; structural health monitoring for bridges; and asset management (whole-life value-based decision making). A Smart Cities series of reports is also being produced on King's Cross and London Bridge stations, and on retail areas around stations
- professional engineering teams should be seconded directly into latter stages of significant research projects with the tasks of implementing the benefits from academic research, so that they can be practically and efficiently applied to meet the UK's infrastructure needs. CSIC's highly effective deployment team, which includes secondees from industry, tests, develops and improves the latest sensor technologies on live construction sites and on existing infrastructure. More than 80 field demonstrations have been implemented by CSIC, and training courses have been run to transfer the knowledge immediately to industry

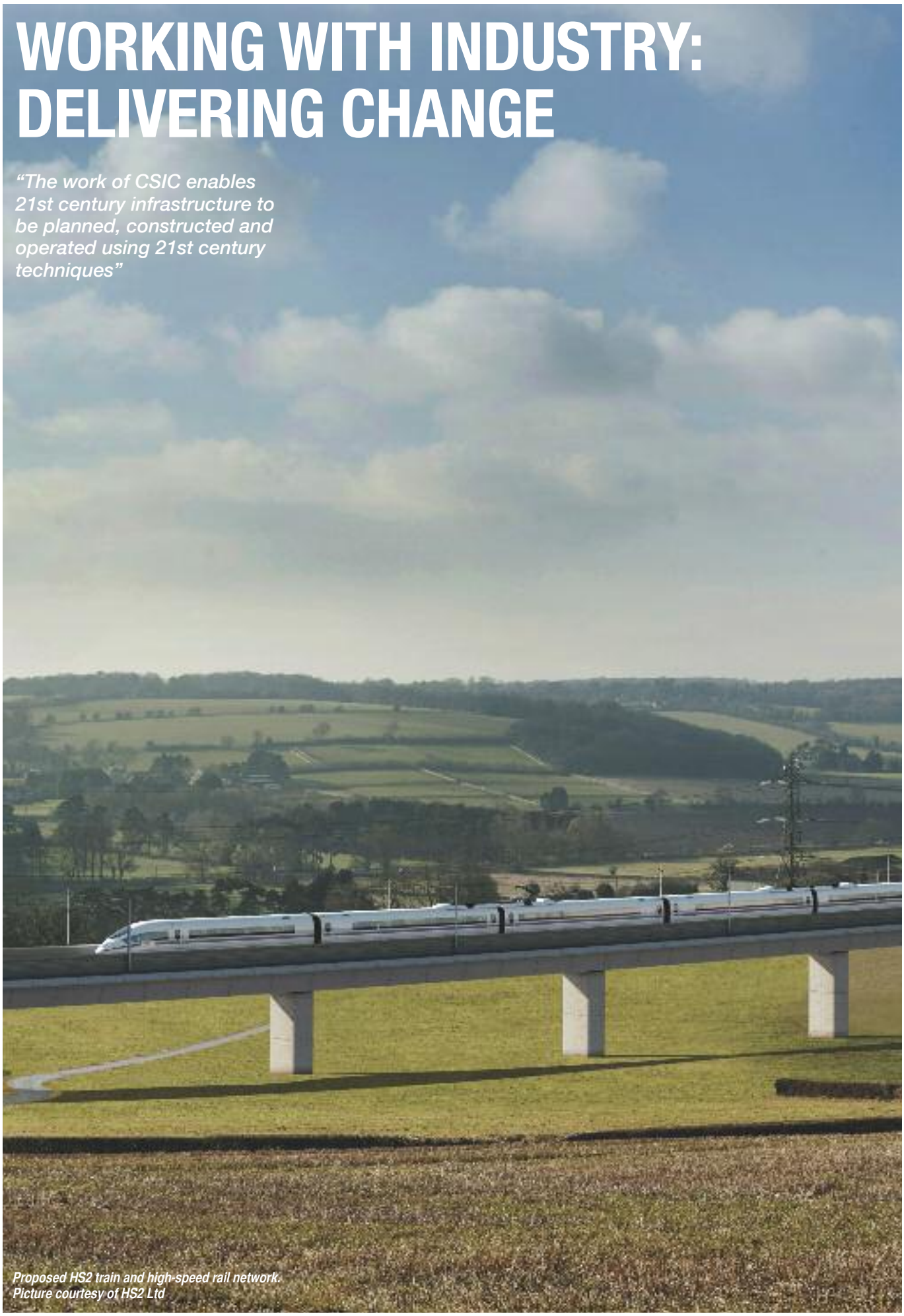
As this *Annual Review* demonstrates, there has been substantial impact of CSIC's activities in terms of the wide variety of technologies (fibre optic strain measurement, UtterBerry ultra-low power wireless sensor motes, and vibration energy harvesting devices) recently deployed on real construction and infrastructure sites. These have been applied to a considerable variety of structures, including Crossrail, National Grid, the Royal Mail Tunnel and CERN tunnels, masonry arches at London Bridge and railway bridges in Staffordshire.

These ground-breaking deployments have involved 41 Industry Partners, and resulted in 20 awards and shortlistings, and more than 600 publications, reports and citations. New approaches to futureproofing of assets have been demonstrated, as well as new methods of modelling and analysing the behaviour of cities. CSIC has also had considerable impact in terms of thought leadership, both in the UK and internationally through keynote lectures, workshops and training courses.

Combined, these achievements are a measure of CSIC's effective commitment to improve the quality and efficiency of our nation's infrastructure.

# WORKING WITH INDUSTRY: DELIVERING CHANGE

*"The work of CSIC enables 21st century infrastructure to be planned, constructed and operated using 21st century techniques"*



*Proposed HS2 train and high-speed rail network. Picture courtesy of HS2 Ltd*

**Professor Andrew McNaughton**
**Technical Director**
**High Speed Two (HS2) Ltd and member of the CSIC Steering Group**

The work of CSIC is taking place at a particularly significant point in Britain's development. It is widely acknowledged by government, industry and society that considerable and continuing investment in infrastructure, in all its forms, is essential for our nation to prosper.

In order to create new and effective infrastructure we must first identify and understand the changing needs of a modern growing country, including new commercial, housing, transport and services construction throughout our major cities. This is incredibly challenging; England is the most densely populated country in the European Union, with precious countryside between our urban centres.

CSIC's output presents opportunities to make major improvements in how we create new infrastructure.

CSIC works closely with Industry Partners to develop technologies and tools to solve industry challenges, offering new approaches to construction based on precise, site-specific instrumentation and measurement, rather than generalised, conservative standards and assumptions.

## World-beating advantages

Adopting smarter methods brings the prospect of improving the efficiency of the construction process through real-time monitoring of condition as construction proceeds, and providing the automated assurance of design and construction without difficult and disruptive testing.

The early implementation of the techniques and tools developed within the CSIC programme offers world-beating advantages to major transport programmes, including HS2 and new water, energy, sewerage and construction projects.

The ability to tailor design and construction precisely to specific ground conditions will lead to savings of cost and resources. Importantly, it will allow work to be completed more efficiently and with greater certainty which means those communities neighbouring construction works should see less disruption over a shorter period of time.

## Continued assurance

Subsequently, the asset owners will have a continuing assurance of performance ensuring only the right maintenance is scheduled at the right time, giving continuing whole-life benefits both for operating cost and maintenance.

CSIC's academic work has always been grounded in a close cooperation with the construction industry – practitioners and asset owners alike. As a result this work has remained firmly focussed on real needs. Together, CSIC and the industry have the opportunity to export this new know-how internationally.

***"Put simply, the work of CSIC enables 21st century infrastructure to be planned, constructed and operated using 21st century techniques. I can speak for the industry in being proud of what CSIC has achieved so far, and look forward to continuing breakthroughs to put this country ahead of the world."***

# ADDRESSING INDUSTRY CHALLENGES AND AMBITIONS

*"By creating, managing and implementing innovations, CSIC continues to lead through example, demonstration and support, enabling industry to exploit novel technical advances at the earliest opportunity to deliver a world-class construction, infrastructure and asset-management industry"*

*CSIC on site at National Grid Power Tunnel, London*

**Dr Jennifer Schooling**
**Director of CSIC**
**University of Cambridge**

Our *Annual Review* showcases another year of great progress for CSIC.

As you will read in this review, CSIC has increased on-site demonstration projects with a further 31 deployments. This is in large part thanks to the efforts of our deployment team – four research engineers, two technicians and four secondees from industry – who have spent much of their time working in challenging conditions to deliver real implementations of CSIC solutions and build industry confidence in the innovations being produced by CSIC and its Industry Partners. CSIC's technologies continue to go from strength to strength, with a win for the Smart Tunnel at the 2014 International Tunnelling Awards, and six other nominations and awards in the last 12 months.

CSIC has matured as an organisation, crystallising our delivery model for translating research into innovation in practice, as shown below (Figure 1).

This model enables us to build on the excellent research taking place in the Department of Engineering here in Cambridge, and also to introduce innovations from Industry Partners and other universities at any point in the process. The key elements to success are:

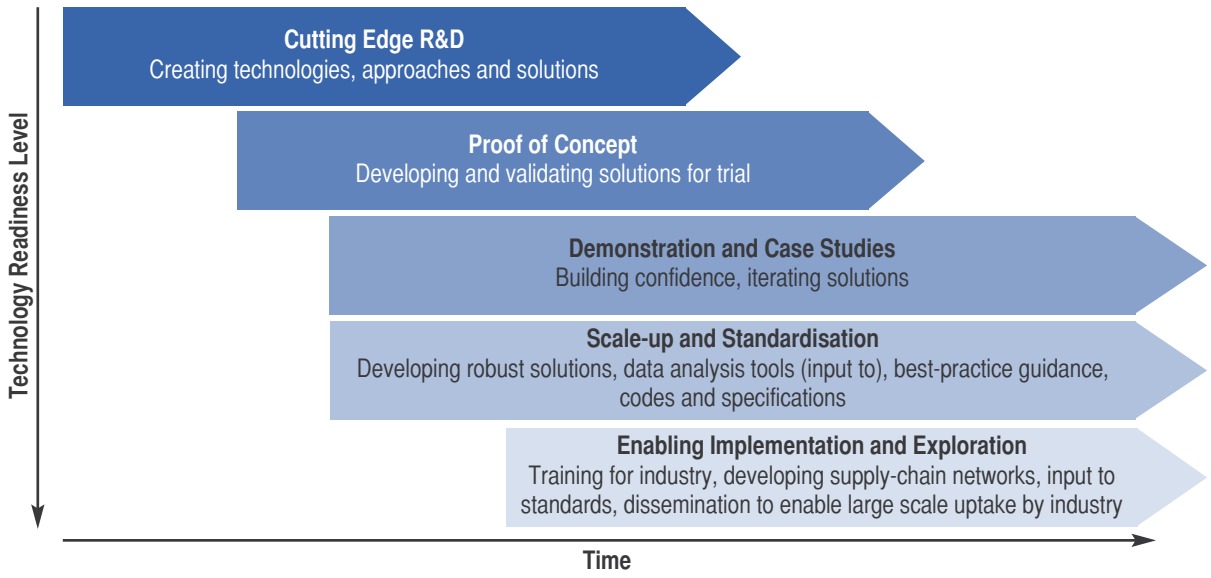
- demonstration – to build industry confidence, and provide feedback to iterate the solutions
- scale-up and standardisation activities – to bring the innovations to a level of maturity that industry can use, including robust hardware, appropriate data analysis tools and frameworks, and best practice guidance
- enabling implementation and exploitation – including raising industry awareness through dissemination, developing training for industry in the use of the innovative techniques and tools, and providing input to standards to enable industry to specify solutions with confidence in the quality of the outcome

CSIC's activities in these areas have grown significantly in the last year; we now have a range of best practice guides in development, which will be published with ICE, and several industry training courses have been delivered.

CSIC is actively working to develop supply chain networks, and is providing workshops on 'Emerging Technologies for Infrastructure and Construction', where solution suppliers and representatives from the infrastructure and construction industries are brought together to explore potential applications. By convening and facilitating events where industry participants can meet and discuss the challenges of their businesses, CSIC creates the opportunity for strategic knowledge to flow between different market sectors, allowing better solutions to be generated.

CSIC continues to focus activity at a range of scales, as shown by Figure 2 (overleaf) which shows the interrelationship between the different physical scales of CSIC's work, and represents the core foundation that our focus on sensors and data analysis and interpretation provides to all our activity.

**Figure 1 – CSIC's delivery model, showing the stages of research translation with increasing technology readiness level and time of an innovation's life cycle**



CSIC takes a whole-life approach to infrastructure, from design to construction, operation, maintenance and decommissioning, focusing on ensuring that the asset provides value throughout its life. All of our activity ultimately aims to transform the future of infrastructure and construction through smarter information – providing decision makers at all points in an asset's lifetime with the information they need to make informed, value-based decisions. The later sections of this review clearly illustrate this with a range of case studies demonstrating the impact CSIC is having on industry.

The last year has also seen CSIC's staff numbers grow. There are now 38 staff and 15 PhD students working in the centre, collaborating with the 12 leading Centre Co-Investigators. In addition, we host summer students and masters students for research projects, which provides a significant opportunity to influence and encourage the next generation of engineers in infrastructure and construction.

In addition to the growth in staff and student numbers, we have been pleased to welcome a number of new CSIC partners over the last year, including CERN, Geotechnical Observations and Topcon, increasing our industry reach and broadening our collaboration.

By creating, managing and implementing innovations, CSIC continues to lead through example, demonstration and support, enabling industry to exploit novel technical advances at the earliest opportunity to deliver a world-class construction, infrastructure and asset-management industry.

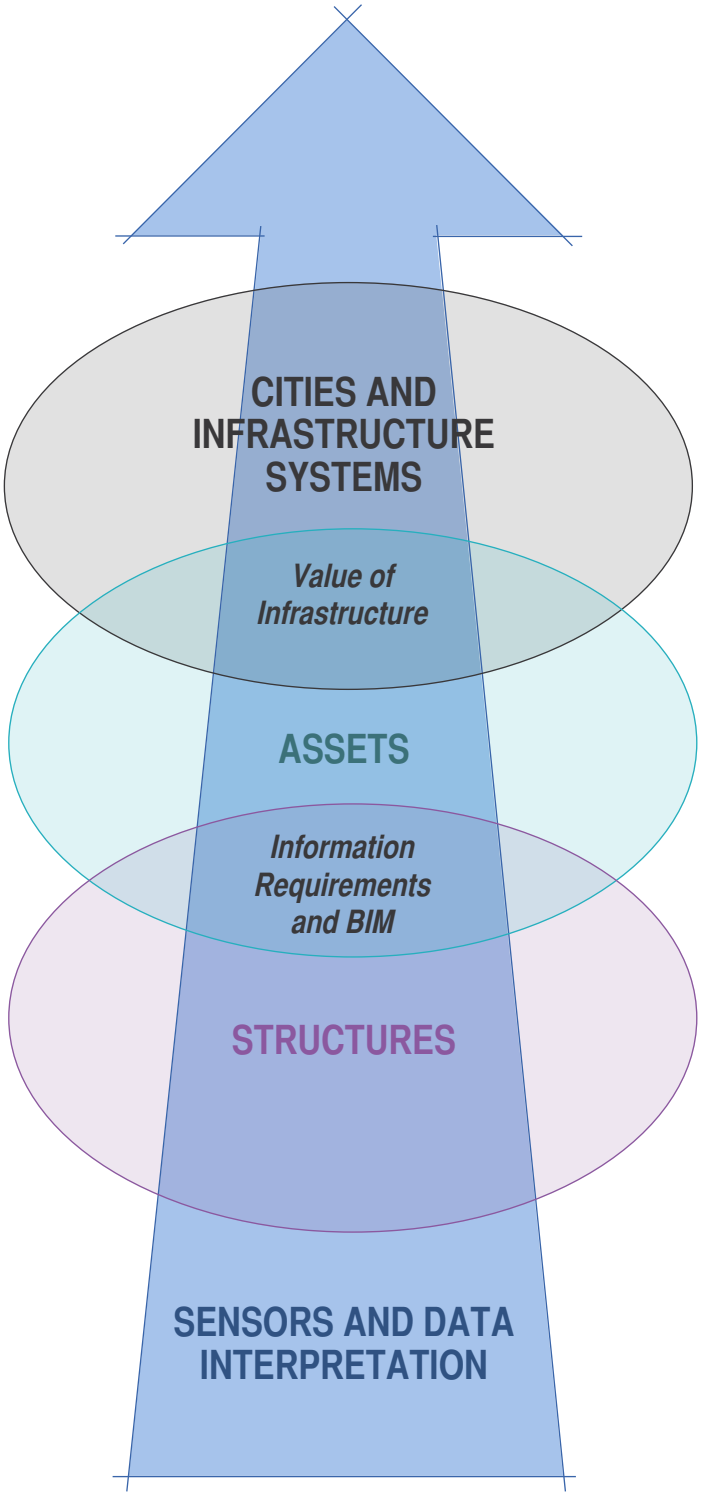



**Figure 2 – CSIC's three spatial scales of activity are underpinned by innovation in sensors and data interpretation**

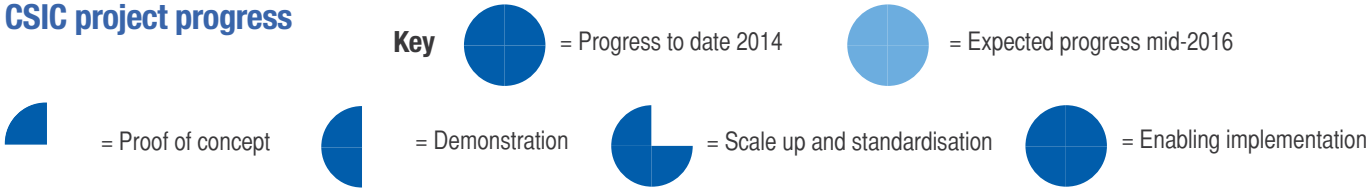
- What economic value does our infrastructure create?
- How does our infrastructure best serve our communities?
- What form should our infrastructure take?

- How do we operate, manage and maintain our assets to deliver best whole-life value?
- How do we futureproof our assets against changing requirements and against shocks?
- What decisions do we need to take to do so?
- What information do we need to make those decisions?

- How do we best design, construct and monitor our structures to deliver the performance we need?
- What data do we need to do this, and how do we interpret it?

- What sensors are needed to measure the performance of our structures, assets and cities?
- How can we make them robust?
- How do we analyse the data to give reliable, meaningful results?

## CSIC project progress




| Technology | Basic readiness | Cities and systems | Rail | Road | Water | Energy | Flood defences | Waste and resources | Buildings |
|---|---|---|---|---|---|---|---|---|---|
| Demand forecasting | | | | | | | | | |
| Infrastructure planning tools | | | | | | | | | |
| Real-time pedestrian monitoring | | | | | | | | | |
| Adaptive zoning | | | | | | | | | |
| Whole-life management of infrastructure assets | | | | | | | | | |
| Futureproofing methods | | | | | | | | | |
| BIM (Building information modelling) level 3 for structural health monitoring | | | | | | | | | |
| 3D digital model creation | | | | | | | | | |
| Deployment projects | | | | | | | | | |
| Wireless sensor networks protocols | | | | | | | | | |
| Wireless sensor networks hardware | | | | | | | | | |
| Lightweight, low-cost fibre optic analyser | | | | | | | | | |
| Fibre optics for structural health monitoring | | | | | | | | | |
| Fibre optics for construction monitoring | | | | | | | | | |
| Fibre optics for performance-based design | | | | | | | | | |
| Digital image correlation | | | | | | | | | |
| Computer vision for change detection | | | | | | | | | |
| Vibration energy harvesting | | | | | | | | | |

# STRUCTURED SUCCESS: APPLYING INNOVATIVE TOOLS AND TECHNOLOGIES

**Professor Kenichi Soga**
**Co-Investigator, CSIC**
**Professor of Civil Engineering**
**University of Cambridge**

CSIC is unrivalled in its development of emerging and innovative sensor technologies, deploying them at some of the UK's largest infrastructure projects including Crossrail, National Grid and the Staffordshire Alliance.

As an international centre of excellence in sensors, CSIC leads the way in deploying and testing new technologies to detect and monitor infrastructure performance and anomalies.

CSIC is more than a think tank – it turns theory into action, trialling new innovative sensor technologies and data interpretation methods at real field sites and building industry confidence in new technologies. This year, we have conducted more than 30 field demonstrations.

## CSIC'S sensing technologies

CSIC does not rely on any single technology but works on a variety to find the appropriate device or set of technologies for specific industry applications. This year:

- CSIC has trialled various fibre optic sensing technologies using commercially available analysers (e.g. Brillouin, Raman and Fibre Bragg techniques) but is also currently developing our own analysers specifically for civil engineering applications
- CSIC has developed different wireless sensor network (WSN) systems. UtterBerry is a highly optimised WSN system with a closed architecture. CSIC has also developed an open source WSN system; the communication software is open source and the hardware information is available to the public
- CSIC has prototyped a new vibration energy harvester, and launched a new start-up with venture capital investment

## Data interpretation

CSIC provides ideas for new engineering interpretation, which are required because new sensors often produce engineering datasets not previously available. For example, some fibre optic technologies provide a continuous set of strain data along the fibre optic cable embedded in or attached to the structures. Engineers are familiar with point-wise displacement or strain data at selected points of the structures. However, the new continuous data requires a different approach to look at how the structures are behaving – more data means more thinking is needed to make the data useful.

Secondees from industry are helping CSIC to develop a new thinking process that is of direct use to engineering practice. The combination of new sensors with new data interpretation is the unique selling point of CSIC.

CSIC continues to invest in developing and deploying new technologies as a community of innovators. We are now producing spin-out companies including, for example, a new vibration energy harvesting company, 8Power, which features the parametric resonance IP developed by CSIC researchers. CSIC collaborates with Industry Partners to create intellectual property and commercial products, including a recently filed patent on fibre optic technology (with Skanska and Arup) and our Smart Foundation software.

The following pages highlight some of our achievements and impact.

## The UtterBerry wireless sensors for civil infrastructure monitoring

**Heba Bevan**

*Heba Bevan, inventor of the UtterBerry at the Eleanor Street shaft, London Borough of Tower Hamlets*

### The technology

UtterBerry sensors are miniature, wireless, ultra-low power sensors combined with artificial intelligence, specifically designed for infrastructure monitoring.

UtterBerry is easily installed in unsafe or difficult-to-access sites to perform on-board calculations deriving acceleration, inclination and displacement in real-time without human intervention.

Sensors are self-calibrating and optimise their data communications within the sensor network according to conditions. They collect, process, interpret and analyse data, reporting it to users remotely on any internet-enabled device.

### Applications

April 2014 marked the first commercial application of UtterBerry at a closed shaft at Crossrail's Eleanor Street site in London. Contractors needed to monitor the area during excavation work and the UtterBerry system was installed in one day by one person.

The technology enabled surveyors to safely monitor the tunnel from their offices. Data was available immediately, including temperature and humidity readings that flagged up the presence of water in the shaft, helping to identify a broken pump.

### Impact and benefits

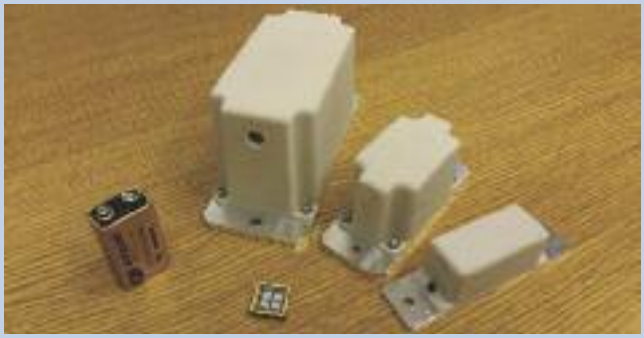
- safety – wireless capability means no personnel are required to enter potentially unsafe environments after installation
- accuracy – high levels of accuracy and repeatability of acceleration, tilt and displacement data have been achieved
- low power – the smallest, lowest power consumption and intelligent monitoring option on the market
- speed and ease of installation – lightweight and small size
- robustness – sensors strong enough to meet all conditions
- longevity – can be deployed for years without maintenance or battery changes

*"The UtterBerry system is an innovation that could become the standard for future monitoring across the construction industry. It is 100 per cent remote, uses almost no power, is very robust, highly accurate and was cheaper than both the traditional alternatives for its application at the Eleanor Street site. There's no doubt it could be used in many different applications."*

Nigel Marsh, Senior Surveyor at Costain

## Vibration energy harvesting

**Yu Jia, Ashwin Seshia**



*Vibration energy harvesting sensors*

### The technology

CSIC's innovative vibration energy harvesting (VEH) and low-power sensing technologies enable a new approach to distributed autonomous structural health monitoring.

The VEH technologies complement or replace existing battery solutions, providing enabling technology for long-term condition monitoring of assets in a range of remote and/or inaccessible locations.

Vibration energy harvesting can potentially provide a convenient, self-sustaining on-board power solution to complement emerging wireless sensor technologies – the smarter power backbone to the ever-growing wireless infrastructure.

### Applications

These devices address a number of applications for wireless sensors in structural health monitoring, industrial process control and environmental monitoring. The team is currently engaged in integrating the harvesters with a variety of wireless sensor modules for monitoring transport-related infrastructure such as bridges and rail track. A significant deployment is planned for the Forth Road Bridge in Scotland later this year.

### Impact and benefits

- fully packaged macro-scale vibration energy harvesters based on the principle of parametric resonance have undergone successful laboratory tests demonstrating peak power output of greater than 100mW. Ongoing work is addressing integration with wireless sensors and preliminary field trials with Industry Partners
- MEMS-scale harvesters have been developed with peak power output of up to 20$\mu$W with a design pathway outlined towards achieving peak output power of greater than 100$\mu$W
- MEMS-scale harvesters have been utilised to successfully power interface circuits for a MEMS strain gauge enabling the possibility of self-powered sensors and 'event-triggered' operations for wireless motes
- patents underlying this technology have been filed through Cambridge Enterprise and a spin-out company, 8Power, is being formed to commercialise the technology
- the team has been awarded a new Innovate UK project to develop the MEMS-scale vibration energy harvesting technology

*"The new vibration energy harvesting technology developed by CSIC is a world-class innovation with several large potential markets. A key benefit of CSIC is the level of contacts and insight the team has developed. This will be of great value as we build the business case for the spin-out 8Power."*

Robert Trezona, IP Group plc

# Impact of fibre optic technologies

**Kenichi Soga, Robert Mair**


*On-site splicing of fibre optic cable at the James Dyson Building, Department of Engineering, University of Cambridge. Picture courtesy of Darren Carter, Morgan Sindall*

## The technology

The use of distributed fibre optic (FO) sensors for the monitoring of civil structures and infrastructure opens exciting new possibilities unmatched in conventional sensor systems.

Engineering design limits are often based on strain and/or stress developing in the structure. For structures interacting with soil (e.g. underground infrastructure such as foundations, tunnels or pipelines), the ground loads are distributed spatially (not point loads); therefore the state of the structure cannot be fully understood unless the complete in situ strain regime is known.

The use of a single optical fibre with a length of up to tens of kilometres of continuous sensing elements makes it possible to obtain a body of invaluable information on the strain and temperature distribution in civil infrastructure assets. CSIC has developed data interpretation methods that utilise new continuous data for engineering assessment of piles, tunnels, retaining walls, pipelines, slopes and bridges.

In collaboration with Industry Partners, CSIC is developing a FO application methodology that is applicable to civil engineering structures. It considers the whole-life cycle of FO monitoring from planning, deployment, operation and decommissioning. CSIC is also producing a FO guidance document, which will be available from ICE, publishing in late 2015.

## Applications

CSIC's fibre optic technologies have been applied to provide insights into structural performance and design, to monitor the construction process and for structural health monitoring. In the last year, applications included understanding sprayed concrete linings in Crossrail's London Liverpool Street Station and instrumenting concrete tunnels in CERN and piles and buttress walls at the London Bridge Station redevelopment.

## Impact and benefits

- the distributed FO technology for measuring strains and temperatures provides a unique dataset, which engineers did not have before
- applied to piles, FO technology will provide displacement profiles along the pile enabling the soil-pile interaction to be evaluated more accurately. Anomalies inside the piles that may influence the overall pile performance are also identified
- the material of optical fibre is silica, which lasts for decades. When the cable is embedded in structures during the manufacturing process, the sensors will remain operational for many years
- the analyser, which is external to the structure, can be evolved over time to provide continual improvements in the quality of the data gathered
- the potential impact of this technology for civil infrastructure design, construction and maintenance is significant, providing asset owners and engineers with new data that has not been accessible until now

New data sets present new challenges – we must now decide how data will be interpreted and used for smarter design, construction and maintenance of civil engineering infrastructure.

***"I've worked with CSIC over the past four years to implement fibre optics into pile testing. The continuous strain enables an impressively detailed understanding of load transfer from the pile to the soil, which is extremely useful in multi layered soils such as those encountered in the Canary Wharf site in East London. Another advantage is that fibre optics take up very little space in a congested pile compared with conventional instrumentation systems. We see many exciting opportunities for piling applications in the future."***

**Duncan Nicholson, Director, Arup**

# UNDERSTANDING STRUCTURES

## New technologies create CSIC's Smart Tunnel

**Mehdi Alhaddad, Matthew Wilcock, C.Y.Gue, Heba Bevan**

### The project

Hundreds of kilometres of London's tunnel and pipe infrastructure are made of cast iron and many London Underground tunnels are now between 50 and 150 years old. Better assessment of their condition has become an increasingly significant issue for maintenance and calculation of residual life.

Currently new tunnels are being built close to London's ageing tunnel network. CSIC Industry Partner, Crossrail, is in the process of building a £15 billion subterranean rail link crossing the city over a distance of around 21km. This project has presented new engineering challenges – never before have new tunnels been dug in London so close, parallel and perpendicular to existing tunnels over such a long distance.

Crossrail engineers faced uncertainty about the likely modes and levels of deformation of existing tunnels. In this case, no one technology could provide the required mode of deformation information for Crossrail. CSIC combined a selection of devices to collect the data.

As cities grow, there will be a pressing need to build new structures close to existing pieces of infrastructure, both in the UK and abroad.

### Applications

Working with Industry Partners Arup, CH2M HILL and iMETRUM, CSIC deployed a team of researchers to install four different pioneering monitoring devices at specific locations inside a 40-metre stretch of the disused, 100-year-old Royal Mail tunnel, at Crossrail's Liverpool Street Station, where the new tunnel was being constructed parallel beneath it.

The same technologies were also deployed at London Underground's Bond Street Station Upgrade project, where a new tunnel is currently being excavated by the Costain/Laing O'Rourke joint venture, perpendicular to and actually touching the Royal Mail tunnel above.

The latter conditions presented an opportunity for CSIC to measure the performance of an existing tunnel in an extreme engineering scenario and data is currently being collected and collated.

The monitoring devices deployed include:

- wireless sensor network (WSN) displacement transducers
- fibre optic strain sensors
- wireless linear potentiometric displacement transducers (LPDTs)
- photogrammetric monitoring

CSIC's bespoke combination of different devices, featuring existing instrumentation currently used by industry and new image correlation techniques, including CSattAR Photogrammetric Monitoring – a new digital image correlation (DIC) technology – captured the various strains and modes of deformation and, in addition, provided valuable comparative data.

This combined instrumentation created a unique 'Smart Tunnel' capable of measuring and monitoring the structural performance and stress levels of the older tunnel as the new, large Crossrail tunnels were excavated immediately below.

*Filming of the installation of CSattAR photogrammetric technology in the Royal Mail cast iron tunnel, London*

### Impact and benefits

The impact of CSIC's Smart Tunnel monitoring has delivered measurable benefit to asset owners:

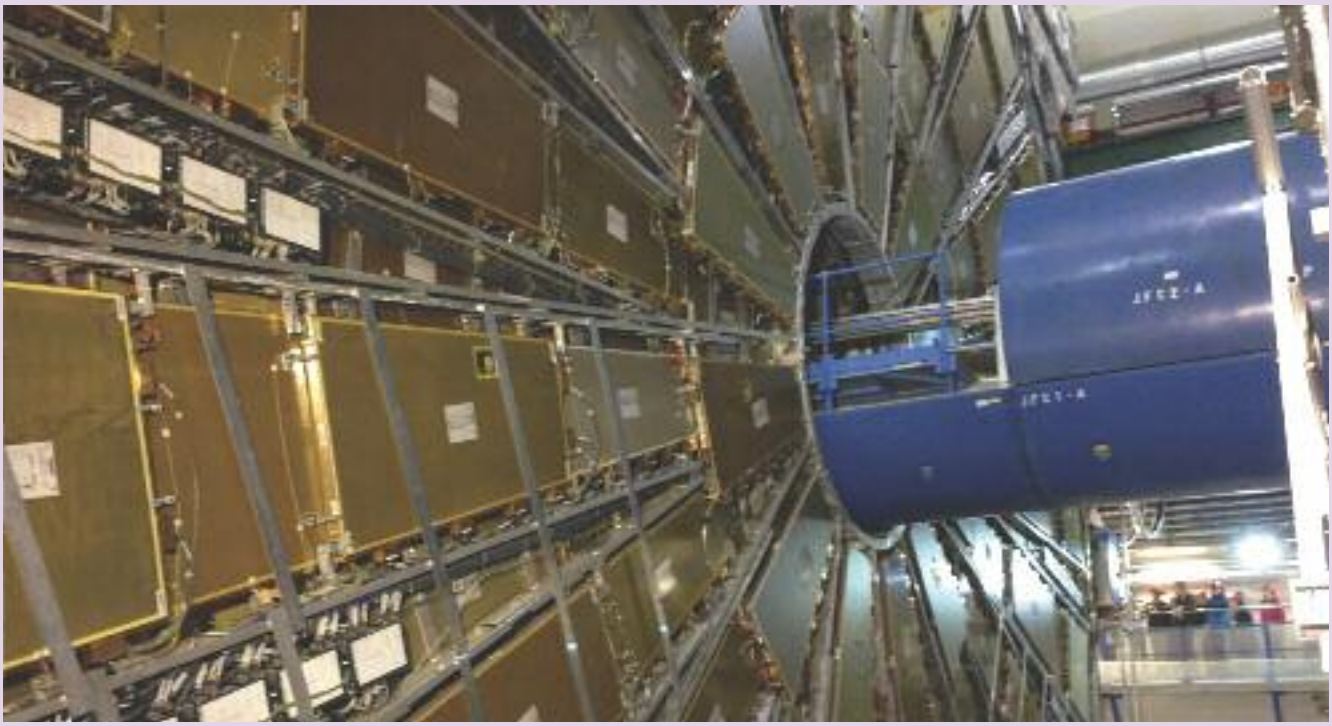
- the digital image correlation technique measured tunnel movements at sub-millimetre scale using digital images taken at different times
- the joint movement and bolt strain measurement techniques provided new insights in terms of joint movements, which have never been measured in such detail before
- the data from the fibre optic distributed strain measurement gave the overall distortion of the tunnels
- the wireless sensor motes measured tunnel movements in three-dimensional directions
- these insights deliver valuable, accurate and validated information to the asset owner enabling better-informed decisions on the effects of new excavation on existing structures
- the combination and deployment of CSIC's advanced sensing technologies allows us to understand the engineering performance of cast iron tunnels, which exist in many parts of London
- the knowledge gained from this project will be shared with asset owners and industry to assess other cast iron tunnels in London, to build safe and long-lasting tunnels for the future and, ultimately, deliver benefit to clients, contractors and tax payers

*"CSIC's monitoring technologies assisted in understanding the deformation mechanism of a number of cast iron tunnels subjected to tunnelling induced movements. Prior to the trials these deformation mechanisms were not well understood. The success of these trials, and in particular the photogrammetry, has led Arup to further develop its relationship with CSIC. This has led to the intent to commercialise the photogrammetry monitoring technique under the name CSattAR. The cost advantage and improved risk management that photogrammetry offers has generated significant interest with a number of potential monitoring contractor customers."*

Mike Devriendt, Associate Director, Arup

# CSIC and CERN: monitoring science and innovation

**Kenichi Soga, Cedric Kechavarzi, Loizos Pelecanos**



*The ATLAS detector, one of the particle detector experiments constructed at the Large Hadron Collider (LHC), CERN*

## The project

CSIC is currently working in collaboration with Industry Partner CERN and Arup engineers to identify suitable remote monitoring technologies to help maintain tunnels and other infrastructure at the European Organisation for Nuclear Research, in Switzerland, which are showing some signs of movement at certain sections.

The radioactive environment inside the tunnels makes several conventional monitoring technologies unsuitable for long-term monitoring as the radiation affects their performance.

CERN has a variety of tunnels with a total length of approximately 80km. A 27km ring tunnel, constructed in the 1980s, houses the Large Hadron Collider (LHC), the world's largest and most powerful particle accelerator. Access at many sections of the tunnels is limited due to the radioactive environment making maintenance difficult. With certain tunnel sections showing some signs of movement, long-term monitoring is essential, but effective maintenance requires a better understanding of the long-term behaviour of the tunnels.

## Applications

CSIC is monitoring critical sections of the tunnels and underground caverns using distributed fibre optic sensing, 3D laser scanning and computer vision technology.

CSIC's monitoring delivers a long-term commitment to providing continuous data about the structural health of the CERN tunnels. CSIC's technologies are robust enough to survive the extremely demanding environmental conditions and present minimal maintenance costs. The ability to offer spatially continuous data builds confidence about the current and future condition of the underground structures.

To date, two tunnel sections and an underground cavern have been instrumented and are being monitored with CSIC technologies. This project will continue until late 2017 and the CSIC team is training CERN engineers to ensure the monitoring and maintenance programme can continue autonomously. Six Arup and CERN engineers attended a two-day CSIC course on fibre optic sensing in Cambridge in December 2014, followed by on-site training at CERN in February 2015.

## Impact and benefits

- the installed sensors provide long-term sensing data of CERN assets and create a database of infrastructure behavioural patterns. This will be coupled with engineering analysis of long-term performance of CERN tunnels conducted by CSIC researchers
- CERN will know if its assets can survive under extreme radiation conditions during the operation of the experiments
- CSIC's fibre optic technologies offer a cost-effective solution as there is minimal maintenance cost of the fibres and a comparatively low operative cost of the fibre optic analysers
- civil engineers will be able to better understand the long-term behaviour of tunnels and underground structures over their entire life history and additionally investigate how these structures respond to radioactivity

***"It is a credit to your team that CSIC was able to complete an installation in such a complex environment having never visited before. It says a lot about the team's skill that at no time was the intervention disruptive to the Atlas team and in no way impacted on the CERN operations. I am really looking forward to the results from this particular trial and hope that we can expand the installation in the near future."***

**Richard Morton, Civil Engineer, CERN**

# Impact of fibre optic measurements in segmental tunnel linings for National Grid and Crossrail

Matthew Wilcock, Saleta Gil-Lorenzo, Mohammed Elshafie, Kenichi Soga

*Tunnel lining segments awaiting installation in the National Grid Power Tunnel*

## The projects

CSIC has worked on two projects this year to embed fibre optic cables in tunnel segments, to provide improved understanding of the performance of the segments during installation and operation.

The first project, on National Grid's new 32km power tunnel below London, is a collaboration with Industry Partner Costain. This project involves tunnelling in soft ground with a tunnel-boring machine, with rapid installation of the concrete ring segments inside the machine. As the lining comes out from the machine, the annulus between the ring and the soil is filled with pressurised grout. Simultaneously the machine pushes against the end of the installed ring to move forward.

The second project is a collaboration with Hochtief on the Crossrail tunnel contract 310, from Plumstead to North Woolwich, where the tunnels are mainly constructed in chalk (most tunnels in central London are built in London Clay/Lambeth Group) with a large water head above it at the deepest point, where the tunnels run under the River Thames.

## Applications

At the National Grid site, CSIC's fibre optics are providing insights into the complex loads applied to the linings during construction. By building a detailed picture at all stages, CSIC will elucidate the nature and magnitude of the loading applied to the segments 'from cradle to grave'. This will provide unique and invaluable information of tunnel lining performance to industry and help optimise future designs.

At the Hochtief/Crossrail project, CSIC's combined instrumentation has accurately measured and monitored the behaviour of tunnel segments in chalk, the effect of loading caused by tidal changes, and the behaviour at cross passages connecting the two running tunnels. This has provided new data at a level of detail that has, until now, not been available to industry.

## Impact and benefits

By introducing instrumentation at the start of construction, CSIC was able to collect data regarding complex construction loading:

- at the curing stage in the factory
- during transportation
- throughout the entire tunnel construction process
- during cross passage construction

This data:

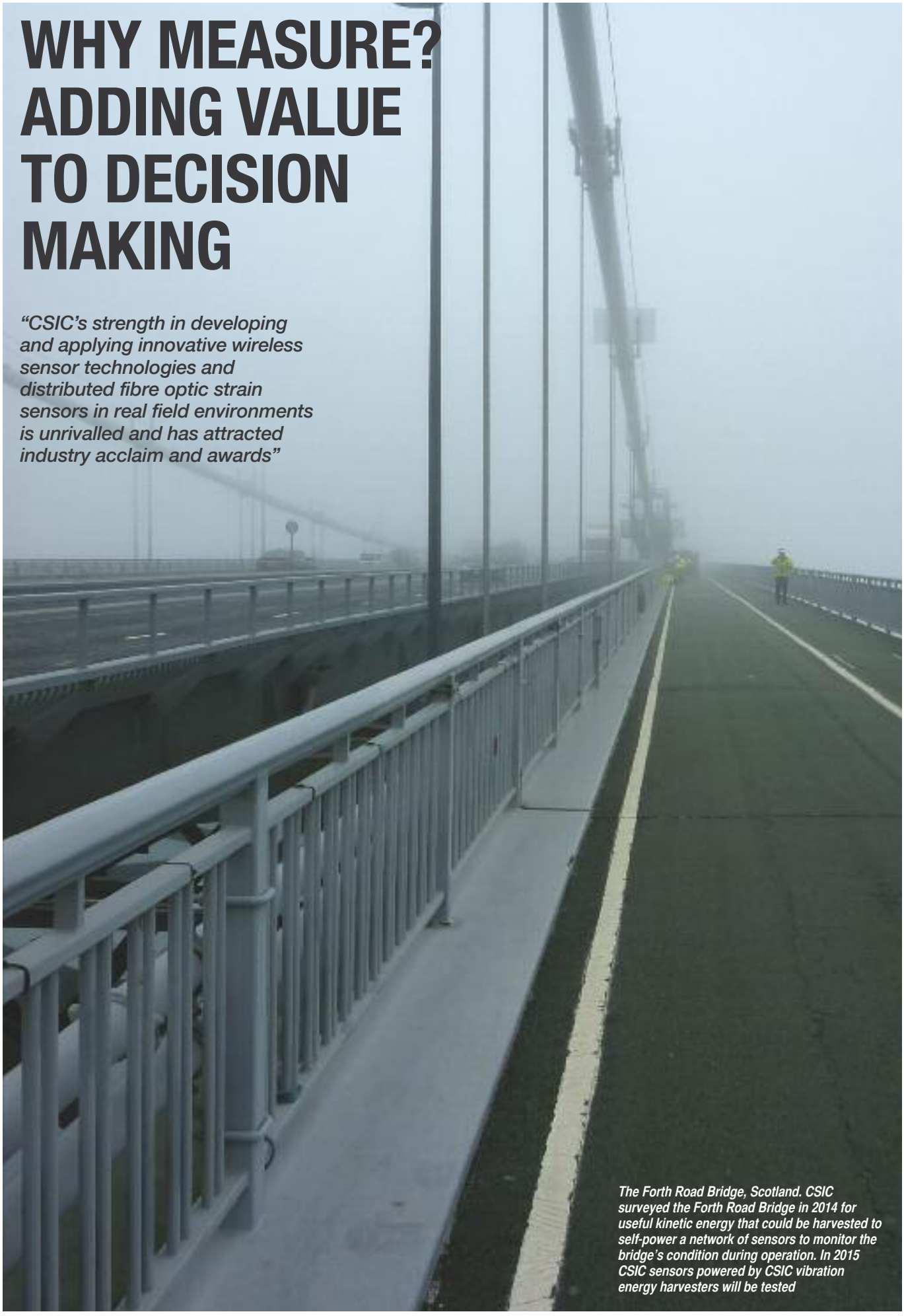
- provides insights into the behaviour of tunnel segments
- informs optimised future designs

*"National Grid, through the London Power Tunnels project, is delighted to facilitate the pioneering work being carried out by CSIC on both the Fibre Optic Strain Sensing and the Computer Vision research and development projects. Developing new technology and methods for monitoring the structural health of tunnels is expected to be of great benefit to National Grid in the future, using techniques that can potentially be further adapted to a broad range of infrastructure asset monitoring. CSIC has demonstrated a high level of ingenuity and endeavour and we look forward to working with them to the successful completion of the projects."*

Mark Farmer, Project Engineer, London Power Tunnels, National Grid

# WHY MEASURE? ADDING VALUE TO DECISION MAKING

*"CSIC's strength in developing and applying innovative wireless sensor technologies and distributed fibre optic strain sensors in real field environments is unrivalled and has attracted industry acclaim and awards"*



*The Forth Road Bridge, Scotland. CSIC surveyed the Forth Road Bridge in 2014 for useful kinetic energy that could be harvested to self-power a network of sensors to monitor the bridge's condition during operation. In 2015 CSIC sensors powered by CSIC vibration energy harvesters will be tested*

**Professor Campbell Middleton**
**Co-Investigator, CSIC**
**Laing O'Rourke Professor of Construction Engineering**
**University of Cambridge**

Currently there are demands for hundreds of billions of pounds to be spent repairing and maintaining bridges around the world. Converting our critical bridges into 'smarter' bridges offers the opportunity to significantly reduce the expenditure needed by providing the key information to prioritise investment in upgrading these structures.

A key objective of CSIC is to provide the evidence base to support decision making when owners and operators make choices in relation to infrastructure investment. In particular, our goal is to answer the key questions of whether a structure is safe, is it performing as expected and required, is any intervention or maintenance needed and how long will the structure last?

The last 10 years have seen significant developments in sensor technology with an attendant increase in the monitoring of structures. In particular, a number of critical elements within our national transport infrastructure, such as tunnels and bridges, are being monitored to validate their performance, help inform maintenance strategies and warn of any potential problems due to damage or deterioration.

CSIC's strength in developing and applying innovative wireless sensor technologies and distributed fibre optic strain sensors in real field environments is unrivalled and has attracted industry acclaim and awards. But building on this success requires constant focus on the value of our technologies to the end users; and one of the questions we are researching at CSIC is how do we demonstrate the benefits – the value – that such systems deliver?

On a new construction site, monitoring is often used to check for deformations of adjacent existing structures to give warning of potential damage or to confirm the geometry or stability of elements during erection. Embedding sensors in new structures provides the opportunity to measure performance throughout a structure's life.

However, the benefits to be derived from accumulating such data may not accrue until many years in the future and the beneficiaries may also be others than the original designer, contractor or initial owner. Thus a whole-life perspective on the cost of designing, building and operating a structure is essential if the true benefit of monitoring is to be recognised. In particular, we need to answer the question: why measure?

In recent years, CSIC has been involved with a significant number of structural health monitoring deployments on a range of infrastructure projects of national significance, instrumenting tunnels and geotechnical structures as well as several bridges, including the Humber Bridge and the Hammersmith Flyover, in London.

Measuring undoubtedly offers benefits to the owners and operators of our bridges. On Hammersmith Flyover, our monitoring identified which bearings under the pier supports had locked up and were not performing properly. A wireless sensor network deployed in one anchorage chamber of the Humber Bridge suspension cables identified that the dehumidification systems were not operating optimally and provided the information needed to make significant energy and cost savings. CSIC's deployments clearly show that measurement can directly provide information of value to a range of stakeholders involved with the operation of our infrastructure.

Currently the Centre is instrumenting two new rail-over-road bridges as part of the Staffordshire Alliance, which is a collaboration between CSIC Industry Partners Network Rail, Atkins, Laing O'Rourke and VolkerRail, to improve the West Coast mainline. CSIC is extensively monitoring the Staffordshire bridges to gain a better understanding of the overall performance of the structures and clearly demonstrate the margin of capacity (or safety margin) so they can be utilised to their full potential.

CSIC is already making an impact on industry by delivering a range of new technologies designed to overcome specific engineering challenges and provide valuable information to asset owners.

*The CSIC deployment team at work on the Forth Road Bridge, Scotland*

# ASSETS: MOVING MINDSETS FROM LEAST-COST TO BEST-VALUE APPROACH

**Dr Ajith Parlikad**
**Co-Investigator, CSIC**
**Senior Lecturer Institute for Manufacturing**
**University of Cambridge**

Asset management is of increasing interest to industry. Infrastructure owners face the challenge of balancing cost and risk against a backdrop of decreasing funding and increasing regulation. The infrastructure and construction industry needs new methodologies and tools to support infrastructure managers to secure the best value for money throughout an asset's lifetime.

When the ISO 55000 family of standards on asset management was published in 2014, worldwide attention was brought to through-life management of physical assets, shifting emphasis from minimising cost to realising value.

CSIC's asset management research has helped infrastructure owners in embracing the key message coming from the ISO standard by providing much-needed clarity on determining the value realised from assets from a multi-stakeholder perspective, and how to make value-based asset management decisions.

Over the past year the CSIC Asset Management team has focussed on the development of four decision support tools to further assist asset managers to make smarter and proactive decisions.

CSIC's value-based decision-making tool helps to systematically determine how an asset contributes to the system's value, how its condition can affect that value, and how the value can be managed by making the right decisions. The table below explains how the value-based approach compares to the traditional, cost-based approach.

The second area of focus for the team is information; the quality of asset management decisions rests on the quality of information available to decision makers.

Our information risk assessment tool helps infrastructure owners identify gaps in asset information and determine risks posed by poor-quality information to their business objectives. This tool helps companies to develop an effective business case for data and information quality improvement initiatives.

CSIC's tool allows infrastructure owners and managers to identify retention needs of asset information and assess the risk of information loss in the long-term due to a variety of challenges including deterioration of storage media, inaccessibility of different file formats and software applications.

The Asset Management team's final area of focus has been to understand the challenges in futureproofing infrastructure assets and systems against disruptions over the assets' and systems' long lifecycles. Our infrastructure futureproofing tool helps decision makers in systematic assessment and planning for future needs of infrastructural assets. A set of futureproofing criteria – identified through a series of workshops and engagement with our Industry Partners – is currently providing the guideline for infrastructure futureproofing.

Throughout last year CSIC collaborated with Industry Partners to test and demonstrate our tools on live sites.

These include:

- demonstrating the value-based decision-making tool with: London Underground, to focus on seepage-repair strategy for tunnels; Cambridgeshire County Council, to focus on bridge maintenance prioritisation; and Surrey County Council, to focus on a replacement strategy for highway protection barriers
- information risk assessment of bridges at Cambridgeshire and Hertfordshire County Councils
- information futureproofing of bridges for Hertfordshire County Council and tunnels and pumps at Crossrail
- infrastructure futureproofing assessment at Liverpool Wastewater Treatment Works with Costain and United Utilities as part of the United Utilities Process Alliance joint venture

| | **Cost-based (traditional)** | **Value-based (recommended)** |
|---|---|---|
| Core focus | Cost | Cost, risk, performance |
| Management philosophy | Minimise expenditure while maintaining satisfying performance requirements | Maximise performance and minimise risk while satisfying budgetary constraints |
| Stakeholder focus | Decision maker | All stakeholders of the asset (e.g. owner, operator, user, regulator) |
| Impact on service | Maintain maximum service levels | Explore innovative approaches to improve service levels |
| Difficulty | Well-established body of knowledge | Concepts not well understood in theory and practice |

# Testing the water: infrastructure futureproofing for Liverpool Wastewater Treatment Works

Tariq Masood

*Liverpool Wastewater Treatment Works. Picture courtesy of Liverpool Wastewater Treatment Works*

## The project

CSIC's futureproofing assessment and planning tools assist asset intensive infrastructure companies to:

- develop strategies to futureproof information
- allow decision makers to collect data and secure its long-term availability
- help identify what the lasting value will be for an infrastructure

CSIC's futureproofing tool has been successfully piloted on Liverpool Wastewater Treatment Works (LWwTW) with United Utilities and Costain to meet increasing wastewater treatment demand due to long-term population growth while keeping the River Mersey clean.

The existing wastewater treatment works at Sandon Dock became operational in 1991 and was upgraded to its current form in 2000. As a result the Mersey now sustains a wide range of fish. However, the works needed replacement.

Liverpool Wastewater Treatment Works is a £200 million extension project to keep the Mersey clean for generations to come. Due for completion Spring 2015, the new plant at Wellington Dock will serve around 600,000 residents. The completed plant will be able to cope with 11,000 litres of wastewater a second.

## Action and achievements

CSIC piloted the infrastructure futureproofing tool on LWwTW. We have:

- identified possible future changes that might affect LWwTW infrastructure
- defined futureproofing criteria in the LWwTW infrastructure context i.e. resilience, adaptability, replaceability, reusability, system stability and information replaceability
- assessed various assets of LWwTW infrastructure (e.g. pumps, buildings, piping, screens) against the futureproofing criteria
- defined futureproofing targets against assets
- conducted gap analysis of current and targeted futureproofing goals for assets
- tested usability and usefulness of the infrastructure futureproofing tool

## Impact and benefits

Application of the futureproofing tool has provided direct benefits to LWwTW infrastructure supplying information to support:

- assessment of the suitability of pump, building, piping and screen assets when considering the design of upgrades and new facilities for long-term use and maintenance
- selection of a variety of water and wastewater process asset upgrades
- embedding the infrastructure futureproofing tool/criteria in risk management process/risk register and stakeholder management process/stakeholder map
- driving innovation and improvement in the industry for future projects
- informed decision making
- through-life value benefits
- improved infrastructure futureproofing strategies to enhance resilience of infrastructure to climate change impacts

*"During the past 12 months I have been working with CSIC and been introduced to the concept of infrastructure futureproofing and the benefits it can achieve when developing solutions for use in the water industry. The use of CSIC's infrastructure futureproofing tool provides real value in the assessment of the suitability of assets when considering the design of upgrades and new facilities for long-term use and maintenance. The use of the tool should help with the selection of a variety of water and wastewater process asset upgrades thus helping drive innovation and improvement in the industry for future projects."*

Andy Fielding, Performance Manager for Costain Water Sector

# Bridging the gap: a value-based approach to maintenance

Raj Srinivasan, Phil Catton, Gokcen Yilmaz

*St Ives Bridge, Cambridgeshire, a fifteenth century bridge forming part of the CSIC and Cambridge County Council bridge maintenance portfolio. Picture courtesy of Cambridge News, Cambridge Newspapers Ltd*

## The project

Cambridgeshire County Council is responsible for the maintenance of more than 1500 bridges of various types, ages, and usage patterns across the county. The bridges include some with heritage status and others of strategic importance with very high traffic volume.

## Action and achievements

The council has to determine the annual maintenance tasks required across the bridge portfolio while working with pressing budget constraints; prioritising maintenance activities and justifying expenditure to funders is key. Last year CSIC's Asset Management team worked closely with maintenance engineers and planners at the council to develop a bridge maintenance prioritisation tool to order annual maintenance activities considering:

- the value generated by the task
- the cost of maintenance
- the risks posed by the condition of the bridge to the safety and functionality of the bridge
- factors including heritage status and wider impact on the road network incorporating the needs of all stakeholders

The tool complements a three-phase approach:

- develops a valuation scheme for bridges based on criticality to the network operation
- develops a value-map for the bridge that identifies how the condition of the bridge affects the various value drivers
- uses the value-map and the valuation scheme to quantify the effect of maintenance activities and prioritise activities on the basis of value-for-money

As the Excel-based tool uses a simple scoring scheme, it is practical and easy to understand and implement. Results from CSIC's tool were compared with the council's previous prioritised list for bridges. This offered validation and revealed new data useful for future planning.

## Impact and benefits

CSIC's bridge maintenance prioritisation tool enabled the council to make better-informed decisions:

- helped bridge managers at the council to justify the annual expenditure on bridge maintenance and to clearly prioritise maintenance activities to ensure maximum value for money spent
- engagement with asset managers at the council led to a wider appreciation of the value-based approach to asset management, potentially paving the way for establishing a step-change in the way assets are managed across the council's wider asset portfolio
- could be adapted for use by other councils and bridge owners potentially generating a wide-scale impact

*"The tool will allow us to prioritise the maintenance activities on our bridges annually based on the provision of service to the bridge users, risk to structural integrity, and the cost of maintenance. It provides us with a degree of confidence to justify the expenditure and programming of our highway structures to target our limited resources to the benefit of the local communities."*

Gareth Guest, Area Bridge Manager at Cambridgeshire County Council

# RESHAPING CITIES THROUGH SMART INFRASTRUCTURE


**Dr Ying Jin**
**Co-Investigator, CSIC**
**Senior Lecturer**
**Department of Architecture**
**University of Cambridge**

Cities worldwide face enormous social, political, economic and environmental change. CSIC Cities team is developing and implementing new systems and techniques to help cities embrace change through reshaping infrastructure.

Over the past year our work has focused on methods that apply smart, digital technologies to allow cities to reconfigure usage of the built environment. We have investigated the emerging barriers to the implementation of smart technologies in existing regulations, standards and business practices at the city scale. This will help governments, institutions, businesses and communities to keep in step with rapidly evolving technologies, unleash new sources of funding, and extend inclusive, liveable, green urban areas.

To achieve this, CSIC has worked closely with government agencies and Industry Partners to develop draft standards and to translate our novel modelling techniques into practical solutions for infrastructure investment design and appraisal.

CSIC has been an active part of:

- the British Standards Institute (BSI) Committee for Smart Infrastructure (SDS/001/08). This plays a key role in the International Organisation for Standardisation (ISO) Technical Committee TC268 in drafting standards for smart cities and smart infrastructure
- the BSI steering groups, which published the UK Publicly Accessible Specification PAS180 on the vocabulary for smart cities, PAS182 on digital data concept models for smart cities, and PD 8101 guide to the role of the planning and development process of smart cities
- the UK Smart Cities Advisory Group
- a new BSI initiative to investigate the standards for City Datasets

Our work is attracting international interest. The Cities team convened two workshops on rail-led urban innovation, in Cambridge in April 2014 and San Francisco in October 2014.

Within the UK, the Department for Transport and Transport for London (TfL) has invited CSIC to present our adaptive zoning technique. This technique is a novel way to enlarge the modelled geographic area (to, for example, the whole of the British Isles or even the EU), speed up computer model simulation tests, and account for nationally important traffic on congested local transport links.

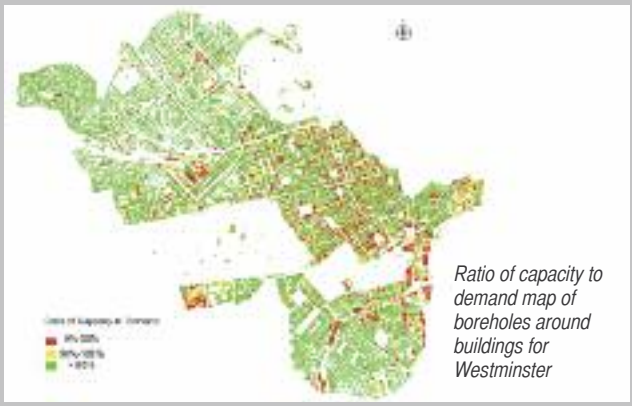
Transport for London has offered data, practical models and advice on policy tests for further research leading to beta-testing of a road traffic assignment model capable of assessing the demand for car, bus, lorry, cycle and pedestrian movements in complex London streets. This work will input into the on-going transformation of roads, land use and associate infrastructure in the UK.

Closer to home, CSIC is part of the Visions and Growth working group of Cambridge Ahead – a business and academic member group dedicated to the successful and sustainable growth of the Cambridge city region.

*Concentration of Foursquare locations in western Europe (December 2014). Image produced by Vassilis Zachariadis, CASA and CSIC*

## Saving energy: ground source heat pump (GSHP) applications at city scale

**Ruchi Choudhary**



*Ratio of capacity to demand map of boreholes around buildings for Westminster*

**The project**
The potential of low-grade geothermal energy for heating and cooling buildings and infrastructure at city scale is being investigated by CSIC with funding from BP. Planning this system at city scale could make a radical step change towards reaching medium to long-term renewable energy and $CO_2$ emission targets.

**Applications**
CSIC has developed a Geographical Information System (GIS)-based city-scale simulation model to estimate how many GSHPs could be installed in the city without losing control of the ground thermal capacity. The novel model is used to quantify the degree to which the system can contribute to meeting building energy demands. The case study is implemented for the whole of the City of Westminster in London.

In the model, building energy loads and thermal properties, underground temperatures and borehole installation designs are structured as fine-grained 3D data maps in order to measure in detail the distribution of GSHP capacity to demand. A highly efficient and robust simulation model results indicating where the highest GSHP potentials are and how to optimise the GSHP installations.

CSIC has also established a future options model for incorporating GSHP in multi-storey business premises and apartments. This model accounts for uncertainties such as energy prices, building energy loads and long-term GSHP performance.

**Impact and benefits**
- city scale planning can make a step change towards reaching medium to long-term renewable energy and $CO_2$ targets
- flexible solutions that embed future GSHP options can significantly contribute to sound financial performance
- CSIC research highlights when to invest in GSHPs, building design and underground space configuration, and the utilisation of low-grade geothermal energy under dense urban areas

***"This study provided a detailed understanding of the links between GIS energy maps, possible layouts for GSHP closed loop boreholes and the ground heat storage system. It shows that GSHP systems can be run in densely populated areas without depleting the geothermal resource."***

Duncan Nicholson, Vice Chairman of the Ground Source Heat Pump Association

## Adaptive zoning: quantifying costs and benefits of major transport investments

**Vassilis Zachariadis**

*Adaptive zoning model of journeys to work in the Greater South East*

**The project**
CSIC research has transformed adaptive zoning from a heuristic spatial modelling tool into a spatial economic method based on robust theories of home and job location choices.

Our new economic interpretation of the adaptive zoning method enables it to be used for appraising the business cases of major transport infrastructure investment projects. CSIC's method is being implemented in a state-of-the-art land-use and spatial equilibrium model that not only tests for the direct effects in reducing car dependency and congestion/overcrowding, but also for indirect impacts including business productivity and housing demand.

**Applications**
CSIC's adaptive zoning approach translates location choice problems, which typically scale by the number of locations squared, into ones of near-linear scalability. Testing on adaptive zoning models of home-to-work trips in Southern England (with 3,250 job and home zones) suggests our technique can be as precise as existing methods with one tenth of computational time and memory.

This step change from existing modelling suites provides a new way to exploit increasing granularity in data on how people choose where to work, live, shop or spend leisure time, and produces more precise simulation of the effects of policy interventions.

**Impact and benefits**
CSIC's new adaptive zoning method:
- enhances spatial economic and transport modelling, making it possible to model in much higher spatial resolutions, while allowing a radically expanded study area and new geo-datasets
- develops significantly more realistic scenarios and produces outputs in a fraction of the time compared with existing models
- opens a new pathway towards cloud-based computing for model applications involving micro-agents

***"Adaptive zoning breaks down long-standing computational barriers and sets new expectations for urban system modelling: to interrogate the national infrastructure as a system-of-systems without losing sight of the role of individual transport infrastructure assets and local planning decisions."***

Dr Alex Hagen-Zanker, University of Surrey

## BSI shaping the future by setting standards for smart cities

**Claudio Martani**

*London Bridge station redevelopment project and the Shard*

**The project**
CSIC has a pivotal role in developing smart cities. CSIC provides new research that feeds the development of a novel and over-arching level of BSI standards for smart cities. These city standards will support effective integration of the physical, digital and human realms to help deliver a sustainable future.

**Applications**
CSIC is actively contributing to the development of Publicly Accepted Specification (PAS) standards and will put these to the test over the next 12 months at a number of selected case study sites of successful rail-led regeneration projects, including areas around London's King's Cross-St Pancras, London Olympic Park-Stratford and London Bridge.

**Impact and benefits**
CSIC case studies will:
- further progress our collaborative standards work with BSI, contributing to further evolution of the publicly available specifications through in-depth case studies and committee work
- provide practical examples and evidence of the role of new standards for smart infrastructure and smart cities in the UK and internationally

*"The work done by CSIC in relation to transport developments will be directly relevant to the forthcoming BSI publication PD 8101 on planning for smart cities. BSI sees continued collaboration with CSIC as a valuable means of ensuring that the knowledge embedded in the standards programme has a firm academic basis. One of the aims of the programme, in line with the objectives of the BIS Smart Cities Forum, is to gain international reputation for the UK's expertise in smart cities."*

Dan Palmer, Head of Market Development at BSI

## Planning and design: reshaping rail station areas in China

**Ying Jin**

*An artist's impression of the planned recreation and business district next to the new high-speed rail station in Nanning, southwest China*

**The project**
CSIC's research on masterplanning and urban design around large rail stations and major public transport hubs has been used by CSIC Industry Partner Chapman Taylor (Shanghai) and Guangxi Hualan Planning & Design Group (Nanning, China) around Nanning high-speed railway station. Nanning, the capital of Guangxi, has just been connected by high-speed rail to the Guangzhou-Hong Kong mega city, which is expected to transform its economy.

**Applications**
This collaboration and ongoing project (which started in 2012) has contributed to the design of a new development zone around the high-speed rail station. CSIC's approach provides a novel model for station area planning, breaking the conventional mould of isolating the station from commercial, institutional and housing development.

The masterplan to develop the station plaza and new Central Business District (CBD) around the station, features CSIC's concepts of infrastructure integration and seamless travel to benefit passengers and generate new commercial value from the infrastructure investment. The Hualan Group is planning a provincial research proposal to utilise the expertise from CSIC in ongoing station area planning and design in 2015.

**Impact and benefits**
CSIC's masterplanning and urban design analytical tools:
- lead to more efficient use of valuable land resources
- enable better capture of land value increases in future infrastructure investment
- help to establish a new business model that integrates transport and property investments

*"China has in the past five years built more than 18,000km of high-speed rail lines. Another 10,000km of high-speed rail lines are under construction or in advanced stages of planning. However, with few exceptions, rail stations are poorly integrated with the existing city and future master plans. It is crucial that new planning and design concepts are introduced to China, and we have enjoyed working with CSIC, using their research to influence real planning and design decisions."*

Lei Hua, Managing Director of Chapman Taylor (Shanghai)

# DELIVERING THOUGHT LEADERSHIP: WORKING WITH INDUSTRY, GOVERNMENT AND ACADEMIA

Delivering impact through thought leadership is integral to CSIC's remit. The ICE's *State of the Nation 2014* report highlights the requirement to deliver capability and capacity and the need for leadership, addressing both the requirement to bring together industry leaders to develop strategic initiatives, and to develop skills in the sector through training and dissemination.

As a world-leading expert in its field, CSIC shares and transfers knowledge through thought leadership workshops and events with industry, government and academia to shape thinking and inform and influence decision makers.

Over the last year, CSIC has held thought leadership events in a number of areas:

## Rail-led urban innovation

CSIC jointly convened a specialist workshop on rail-led urban innovation, in October 2014, with the UK Science and Innovation Network (British Consulate General) in San Francisco, with industry sponsorship from AECOM and Arup.

The workshop engaged closely with major industry players, government agencies and standard setters. CSIC Director Dr Jennifer Schooling and Co-Investigator Dr Ying Jin were among 25 speakers and chairs at the workshop, which provided a rare opportunity for experts to hear the first-hand experience of successful major project delivery and examine common lessons and repeatable solutions to help reshape major cities around the globe.

The workshop considered innovative examples to reshape cities including London, Tokyo, New York and San Francisco. The outcomes will be published as a key reference for building consensus in maximising the societal benefits of rail investment and set new standards for emerging high-density areas around train and metro stations.

## Futureproofing infrastructure assets

Futureproofing our infrastructure assets is increasingly important to industry. Identifying methods to support infrastructure managers to optimise the value of an asset throughout its lifetime is key. CSIC is actively shaping the future of futureproofing and the framework and criteria we have developed are providing new guidelines for industry.

Over the past year, CSIC has brought together futureproofing practitioners and asset managers from a range of infrastructure contexts in two workshops, held in January and April 2014. These events explored the value and the approach for integrating futureproofing into asset management practice, addressing the ability of infrastructure to be resilient to unexpected or uncontrollable events, and to adapt to changing future capacity and usage requirements.

Following CSIC's workshops, the Institute of Asset Management (IAM) annual conference in July 2014 ran a special session on futureproofing, chaired by CSIC's Dr Ajith Parlikad, which has generated interest in this area within the IAM.

***"Our futureproofing workshops attracted delegates from a wide range of infrastructure organisations including London Underground, Costain, IBM, Highways Agency and Infrastructure UK, among others. CSIC's tools and methods are attracting increasing industry attention and put CSIC at the forefront of integrating futureproofing into asset management practice."***

**Dr Ajith Parlikad, Co-Investigator CSIC**

## Bringing together global experts in distributed fibre optic sensing

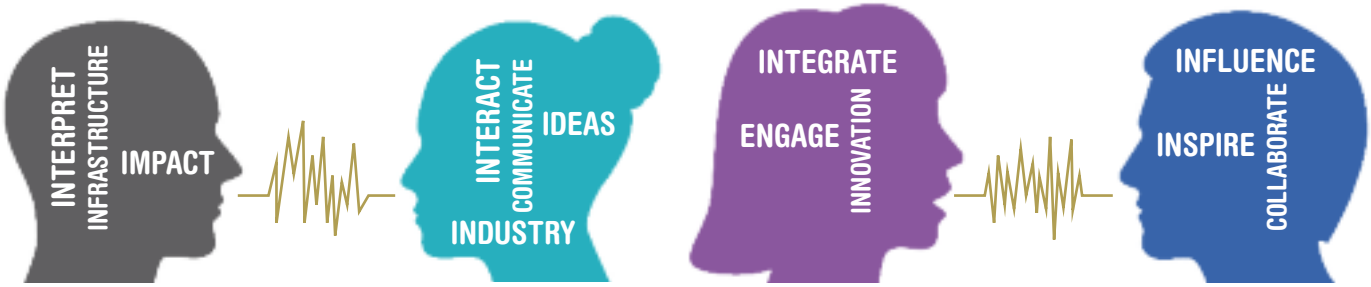
The inaugural Cambridge Conference on Fibre Optic Sensing in Civil Infrastructure (CamFOS) marked another thought leadership first, bringing leading international FOS experts together at the University.

The event, held at Robinson College in June 2014, showcased the latest developments associated with the advances in fibre optic sensing technology together with field deployments; it also demonstrated how fibre optic sensing could deliver value for designers, contractors and clients to realise the transformative benefits of incorporating the technology in civil infrastructure.

The conference created a unique platform to discuss the development of fibre optic sensing in civil engineering and established a dialogue between all the key stakeholders, which will help shape future utilisation of the technology and commercial practice.

***"The Cambridge conference was a unique get-together of all significant experts in the field of fibre optic sensing in civil infrastructure. The right mixture of representatives from academia, instrument manufacturers and civil engineering infrastructure owners provided the perfect basis to develop new ideas for the further advancement of fibre optic monitoring."***

**Professor Werner Lienhart, Head of the Institute of Engineering Geodesy and Measurement System at Graz University of Technology**



# AWARDS, NOMINATIONS AND MEDIA

CSIC sensing technologies have attracted industry acclaim, nominations and awards throughout the year, acknowledging the strength of CSIC's innovative approach and effective collaboration with industry:

- CSIC won the prestigious Ground Investigation and Monitoring Award for the Smart Tunnel and was shortlisted for three separate category awards at the International Tunnelling & Underground Space Awards 2014
- CSIC's Bridging the Knowledge Gap in London's 'Secret Tube' was shortlisted for the British Construction Industry (BCI) Product Design Innovation Award 2014
- The UtterBerry, an intelligent sensing technology developed by CSIC PhD student Heba Bevan, won the Premier Award at the Chartered Institute of Building International Innovation & Research Awards 2014
- The UtterBerry won the Crossrail Best Practice/Innovation Award for contractors Costain-Skanska who deployed the technology at a partially sealed adit complex at its Eleanor Street site in London

## Ongoing success

- Building on this success, CSIC projects and UtterBerry have received no less than six nominations for the Ground Engineering Awards 2015 with the final results scheduled in June
- CSattAR and UtterBerry have been shortlisted in the Company Innovation section of the Construction News Specialist Awards 2015

## In the media

- CSIC made front-page news on the award-winning, monthly flagship magazine of the American Society of Civil Engineers, *Civil Engineering* which reaches an audience of 140,000 civil engineers worldwide
- CSIC's Smart Tunnel featured in the BBC technology flagship programme, *Click*, which was broadcast around the world

***CSIC, winners of the Ground Investigation and Monitoring Award at the 2014 International Tunnelling & Underground Space Awards***

- CSIC's Head, Professor Robert Mair, was interviewed by the *Financial Times* about the effects of London's subterranean building boom
- A video featuring CSIC's work went viral. London Evolution Animation (LEA) attracted more than 350,000 YouTube hits and unprecedented numbers of re-tweets from @guardiancities and @guardian
- CSIC is a monthly contributor to *Infrastructure Intelligence*, the industry go-to independent digital and print title, produced by the Association for Consultancy and Engineering. CSIC produces articles written by members of the team highlighting new technologies, research and industry deployments
- *New Civil Engineer: Where the Smart Money is*, by Ben Cronin. Interview with CSIC Director, Dr Jennifer Schooling and CSIC Business Development Manager, Phil Keenan
- CSIC's Head, Professor Mair and CSIC PhD student Matthew Wilcock talked about the relevance of CSIC's work to government and industry on the Institution of Engineering and Technology (IET) online news programme made in association with ITN Productions, highlighting the importance and relevance of research funded by the Engineering and Physical Sciences Research Council (EPSRC)
- CSIC Head, Professor Robert Mair was a guest speaker at the Hay Festival, one of the most prestigious literary festivals in the world

*"CSIC's articles are among the best read on the* Infrastructure Intelligence *website because they give the infrastructure community insight and advance warning of innovation and new thinking that will change and challenge the sector. From wireless sensing and intelligent infrastructure to the need to consider what is appropriate development, the informative pieces are top reads for our audience."*

Jackie Whitelaw, Associate Editor, *Infrastructure Intelligence*

# DRIVING INNOVATION INTO PRACTICE

*Cedric Kechavarzi (left) and Phil Keenan*

**Phil Keenan**
**Business Development Manager and**
**Cedric Kechavarzi**
**Knowledge Transfer Manager**

CSIC's Business Development and Knowledge Transfer team works closely with industry to identify and understand key issues and challenges in order to design, develop and deliver effective and repeatable solutions.

CSIC's vision to transform the infrastructure and construction industries through smarter information is supported and shaped by our 41 Industry Partners, who bring valuable frontline experience to the working relationship.

This unique collaboration offers benefits and value to both parties as well as the wider infrastructure community; testing our new tools and technologies at real field sites on live projects accelerates the timeframe for these devices to become part of the construction industry mainstream.

CSIC's Business Development and Knowledge Transfer team works across a number of areas to achieve its goals:

## Deployment – providing robust solutions

In 2014 CSIC's Deployment team gathered full strength with four installation engineers joining CSIC, supported by a team of secondees from CSIC Industry Partners including Arup, CH2MHill (Halcrow Group) and Mott MacDonald. Our secondees provide another level of expertise and enable CSIC to vary the skill set in our deployment teams to effectively meet project requirements.

We now have a full complement of engineers and technicians monitoring infrastructure, installing sensors and implementing procedures and protocols, developed by CSIC, at major sites around the UK.

Over the last year this has included:

- Crossrail's Liverpool Street Station and Paddington Station developments where we are monitoring the structures during construction to better understand performance and validate design codes and assumptions
- London Bridge Station Redevelopment, with Industry Partner Costain, where CSIC is applying a range of monitoring techniques to both the existing station structures and new structures
- Victoria and Albert Museum extension, with Industry Partner Arup, where CSIC is conducting tension pile monitoring to understand pile performance
- Norton Bridge, near Stafford, as part of a major upgrade to the West Coast Main Line, working with Industry Partner Laing O'Rourke, instrumenting a new rail-over-road bridge to deliver new insights into how bridges function and respond to load dynamically and to validate structure design

## Developing the value chain

Delivering advanced sensing solutions to the construction industry requires a full value chain to be in place:

- CSIC is working with key technology suppliers, developing the capabilities of installation service companies and working towards standardised installation methods
- CSIC researchers are collaborating with Industry Partners developing new instrumentation and sensors that deliver cost breakthroughs in sensing to provide a better-value proposition
- CSIC is rolling out new technologies that make sensors easier to install and more economical than ever before, including a new prototype distributed strain sensing analyser available later in 2015

## Training and dissemination

Sharing information and knowledge is key to advancing industry adoption of innovative solutions. CSIC is developing a range of routes for disseminating the advances we are making in smart infrastructure and construction, including:

### Specialist training courses

Over the past year, CSIC has developed and delivered a series of specialist one and two-day training courses including a bespoke programme designed for our Industry Partners CERN and Arup covering the techniques required to install and use fibre optic strain sensing for monitoring infrastructure assets.

Other courses delivered include:

- Distributed Optical Fibre Strain Sensing for Geotechnical Infrastructure Monitoring (February 2014)
- Competitive EU proposal & Consortia – Horizon 2020 (July 2014)
- Fibre Bragg Grating Optical Sensing for Structural Health Monitoring (September 2014)
- Automatic Identification (AutoID) for Smart Assets and Cities (October 2014)

### Best practice guides

CSIC is also developing a series of best practice guides to be published in conjunction with the Institution of Civil Engineers (ICE) over the coming year. These guides will cover:

- distributed fibre optic strain sensing
- wireless sensing networks
- structural health monitoring of infrastructure assets
- asset management and monitoring

The guides are intended to be wide-reaching, informing and supporting the construction industry, infrastructure owners and operators, manufacturing, electrical and information sectors in the installation and operation of novel sensing technologies for asset monitoring and management.

### Case studies

CSIC's Cities team is producing additional publications to transfer knowledge to the wider business and academic communities, with a particular focus on planning and development. These documents will be published in conjunction with ICE and RIBA (Royal Institute of British Architects) and rolled out over the next 18 months. The first one is due for release mid-2015.

## Inviting new opportunities

This year also brings new opportunities to CSIC. We will:

- embark upon our first water infrastructure-sensing project using fibre optic sensors and monitoring up to 5km of sewage watercourse for leaks with Severn Trent
- continue to develop demonstrator

projects in a wide variety of new infrastructure asset classes, collaborating with our Industry Partners to demonstrate our capabilities and deliver valuable innovations
- expand our interactions with SMEs, helping them to bring their innovative solutions to the market through focused events with construction and infrastructure sector clients

## Building the future of CSIC

Working with our Industry Partners has enabled CSIC to achieve significant success over the past year, including industry awards, nominations and wide media interest.

CSIC's Business Development and Knowledge Transfer team will continue to build on these achievements in the coming year. This will include:

- delivery of further deployments and case studies in CSIC's technical theme areas to demonstrate technologies and explore new markets
- delivery of robust installation methods in sensing systems including fibre optics (Brillouin, Fibre Bragg, Raman sensing), wireless sensor networks and MEMs technologies
- dissemination of successful implementation of innovations at industry events including the NCE/Ground Engineering conference series in 2015
- continuing to develop CSIC as a nucleating point to assist partner companies to engage and benefit from a range of other innovation-related activities and programmes
- further technology showcase events for supply chain partners to explore novel applications of technology with infrastructure and construction partners
- developing capacity to engage with SMEs and start-ups, exploring specific targeted activities for SMEs

CSIC's work has the potential to transform the infrastructure industry and help the UK become a world leader in the fields of sensing technology, asset management and smart city development. We cannot achieve this alone – working with industry is the key to our success and we always welcome approaches from Industry Partners seeking to collaborate.

As our *Annual Review* demonstrates, CSIC has made significant progress in the past year.

We look forward to working closely and productively with industry to build on this success and share our expertise and experience with a wider community.

## Knowledge exchange on deployment

CSIC has developed a secondment model involving Industry Partners seconding staff to CSIC for a period of six to 12 months. This brings a range of benefits:

- for CSIC – we have access to high quality staff with the relevant industry experience and knowledge, for periods of six to 12 months; dissemination to industry partner organisations through staff working in CSIC and returning to their parent organisations
- for the seconding Industry Partner – an opportunity to develop staff with potential to be exposed to CSIC technologies in more depth, and to bring those skills and knowledge back into the organisation when the secondee returns
- for the secondee – an opportunity to develop a range of skills, contributing to professional development, and participate at the early stages of technology and methodology development

CSIC has been privileged to welcome five secondees over the last 12 months from Industry Partners Aeroflex, Arup, CH2M Hill and Mott MacDonald.

### The secondment

Katie Liu, an engineer with CSIC Industry Partner Mott MacDonald, was seconded to CSIC in June 2014 for six months. Katie worked on a number of projects focussing on utilising fibre optic sensing in field applications and gathering data for analysis to lead to future improved performance-based design and construction processes.

### Applications

As part of the CSIC deployment team, Katie worked on major engineering projects and training activities including:

- Crossrail Liverpool Street Station – assisted in fibre optic installation to study the effect of the breakout of the cross-passage tunnels on a concourse tunnel and data collection on site
- United Utility Shaft, in Manchester – assisted in splicing multiple fibre optic cables installed within the circular shaft to understand hoop stress generated during excavation and data collection
- Crossrail Limmo Shaft – based on the data from fibre optics installed within diaphragm wall panels during excavation and collated by other CSIC colleagues, Katie carried out data analysis using MATLAB to give better understanding on bending, hoop and temperature strains of the shaft. This will contribute to more informed decision making and potential savings in materials, programme and cost in the future

*Katie Liu, Mott MacDonald secondee, on a deployment with CSIC*

- MM Water and Environment – organised meetings between CSIC and the MM Cambridge office with a view to collaboration, knowledge dissemination and broadening the deployment of fibre optics in civil infrastructures in the water environment
- training activities included laboratory sessions, site visits, attending meetings, conferences and health and safety courses

### Impact and benefits

The secondment offered Katie personally, and Mott MacDonald as a company, a range of benefits including:

- a better understanding of fibre optic sensing including testing, data processors and types of fibre and data analysis methodology
- gaining field experience in fibre optic installation including fibre protection, splicing, data gathering and testing
- participating in meetings and conferences attended by international industrial and research groups

***"I feel truly privileged to be seconded to CSIC. It was fantastic to be involved in the deployment of these emergent technologies, on real projects, gathering data that will directly impact upon future construction that my company undertakes."***

**Katie Liu, Engineer, Mott MacDonald**

# CSIC would like to thank our Industry Partners:

## Infrastructure clients (owners and operators)

## Consultants, contractors and asset managers

## Technology and information supply chain

## Knowledge partners

Unless credited all photographs have been provided by staff and students at CSIC, Department of Engineering, University of Cambridge

CSIC Cambridge Centre for **Smart Infrastructure and Construction**

**Email: csic-admin@eng.cam.ac.uk**
**Tel: +44 (0)1223 746976**
**www.centreforsmartinfrastructure.com**
**@CSIC-IKC**

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