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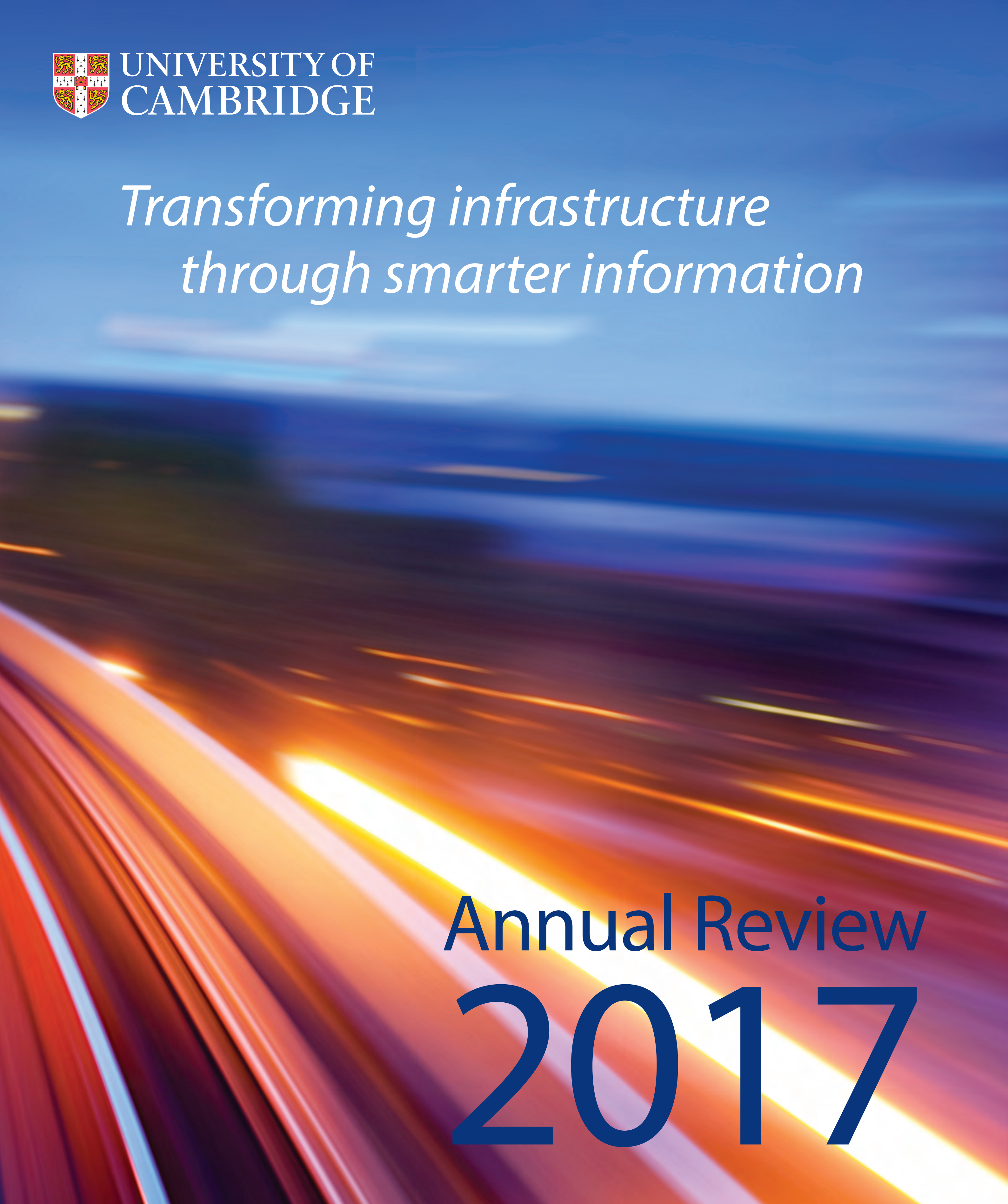

Transforming infrastructure through smarter information

Annual Review 2017

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

CSIC Partners

Infrastructure clients
(owners and operators)

Consultants, contractors and asset managers

Technology and information supply chain

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Preface

Tony Meggs
Chief Executive
Infrastructure and Projects Authority (IPA)

In government, many of our most important policy priorities are delivered through projects of one form or another. Infrastructure projects, such as railways and roads, can boost the economy, improve productivity and raise living standards. The Infrastructure and Projects Authority (IPA) supports their successful delivery.

That is why the IPA takes an interest in collaborative research projects such as the work being led by CSIC. While we know that successful delivery is contingent upon good project management, governance and assurance, the new technologies that CSIC is developing have an increasingly important role in making future projects more effective.

Innovations based on Smart Infrastructure monitoring have the potential to improve performance and value through reducing construction costs, validating design methodologies, improving safety and reducing emissions. For example, CSIC collaborations and demonstrations have already featured in major infrastructure projects such as Crossrail and Thames Tideway Tunnel. Of particular value is the industry participation in CSIC research; there is potential for real, industrial exploitation of the technology and for direct learning to be recycled into subsequent projects.

The IPA is looking at ways the government, working with industry, can help improve the cost, quality and performance of infrastructure. This will build on the work of the 2010 - 2014 Infrastructure Cost Review, which enabled a 15 per cent reduction in the costs of building infrastructure. Because of the importance of new technology and innovations to the successful outcome of major projects and the ongoing operation and maintenance of major infrastructure assets, research projects such as these are an important part of the landscape that we will draw upon as we undertake this review.

CSIC, and other research centres like it, provide us with valuable insight into cutting-edge smart technology that will no doubt play a key role in our future infrastructure.

Songquan Deng/Shutterstock

Introduction

Image courtesy of Paul Milsom on behalf of ICE

Professor Lord Robert Mair CBE
Head of CSIC
University of Cambridge

The Cambridge Centre for Smart Infrastructure and Construction (CSIC), funded by EPSRC, Innovate UK and industry, aims to transform the future of infrastructure through smarter information informing better decision-making. Its principal role is to advance research in Smart Infrastructure and create impact for infrastructure owners, operators, designers, and contractors. CSIC is developing cutting-edge sensing and data analysis models, which will provide a powerful platform for delivering data to enable smarter and proactive asset decisions, both during construction of new infrastructure and for existing infrastructure. This Annual Review presents some of the recent work by CSIC.

The engineering, management, maintenance and upgrading of infrastructure requires fresh thinking to minimise use of materials, energy and labour while still ensuring resilience. This can only be achieved by a full understanding of the performance of the infrastructure, both during its construction and throughout its operating life, through the application of innovative sensor technologies and other emerging technologies. There is a compelling case for using sensing and data analysis to enable smarter, proactive asset management decision-making for our infrastructure. Being proactive, not reactive, enables maintenance, inspection and refurbishment programmes for infrastructure assets to be developed, focusing on condition and preventive maintenance.

As Jennifer Schooling argues in her article in this Review, current UK government initiatives, including the Industrial Strategy Challenge Fund and the Sector Deals, present the infrastructure and construction industry with unprecedented opportunities to collaborate and focus on delivering innovation to our industry. This will lead to better, more certain outcomes using digital technologies, improving productivity, quality and safety, and optimising through-life performance through smarter assets.

It is essential to capture and analyse the right data at the right time for infrastructure asset management decisions to be effective. Being in the midst of a digital revolution, we cannot overestimate the importance of big data. This also has a hugely important part to play in the design, development and management of our future infrastructure. Emerging sensor technologies such as those described in this Review are capable of producing vast amounts of new and important data to provide new understanding, streamlining the health monitoring of the nation's infrastructure. However, this data needs to be managed in an integrated way. Our industry puts a value on physical assets, but not yet on digital assets. As Mark Enzer argues in his article in this Review, as the industry moves forward we must treat data as a resource and put a value on information in order to achieve a real digital economy – and an even stronger case for Smart Infrastructure.

An underpinning plank of CSIC's operations is close collaboration with industry. We work with the infrastructure and construction industry and supporting organisations in a number of different ways.

> Our aim is to employ world-leading research to transform the future of Smart Infrastructure and construction, and initiate industry-collaboration projects to establish the UK as a global leader in this field.

CSIC is already working effectively at a number of scales across academic research, policy, standards and industry, and is uniquely positioned to integrate the skills, people and knowledge to enable industry to target wealth-generating opportunities and meet the challenges that come with transformative change.

Working with CSIC helps industry to optimise opportunity. Sharing information, skills and knowledge is key to advancing industry adoption of innovative solutions to engineering challenges. The case histories and research articles in this Review illustrate how CSIC provides companies operating in the infrastructure and construction sectors with the tools, training and information necessary to take advantage of the latest technical developments in sensor technology and asset management.

Moving forward – seizing the opportunity for change

Dr Jennifer Schooling
Director of CSIC
University of Cambridge

Current UK government initiatives, including the Industrial Strategy Challenge Fund and the Sector Deals, present the infrastructure and construction industries with unprecedented opportunities to collaborate and focus on delivering innovation. Essential to this are Smart Infrastructure solutions that provide better data to inform better decision-making.

Working together as an industry

We are living in unprecedented times of potential for major transformation in the infrastructure and construction industries. A 'digital revolution' is occurring, and it is up to each of us in the industry to assess what impact that has for our business and our sector and, crucially, to pro-actively engage in the agenda.

A concerted coordinated effort is required throughout all levels of the supply chain, as well as an openness to engage with and deploy experience from other sectors. There must be a shift in mindset and understanding, to value digital assets and use them to deliver better outcomes for the people who are the end users of our infrastructure.

CSIC is well placed to help facilitate this effort but no single organisation can act alone. Only by working productively together as an industry can we optimise this opportunity to transform the future of infrastructure and construction.

Seizing the opportunity

It is time to seize this chance to make better use of the abundance of data available to improve our infrastructure and construction industry. This opportunity is not limited to new infrastructure; there is significant potential to improve the condition and management of our existing infrastructure as well. Figure 1 shows how better management and use of data will lead to smarter decisions that enable us to get more from our existing assets, and to schedule informed maintenance interventions when required rather than on a periodic basis. All the main components of digital infrastructure have a place in this simple model. It is the overlay of this model onto physical infrastructure that makes it 'smart'. At the base is raw data and at the apex are better informed decisions – the higher up, the greater the value of information; the lower down, the greater the volume of data. Information processing occurs within each layer, and communication connects both the layers and the outside world to which the information applies.

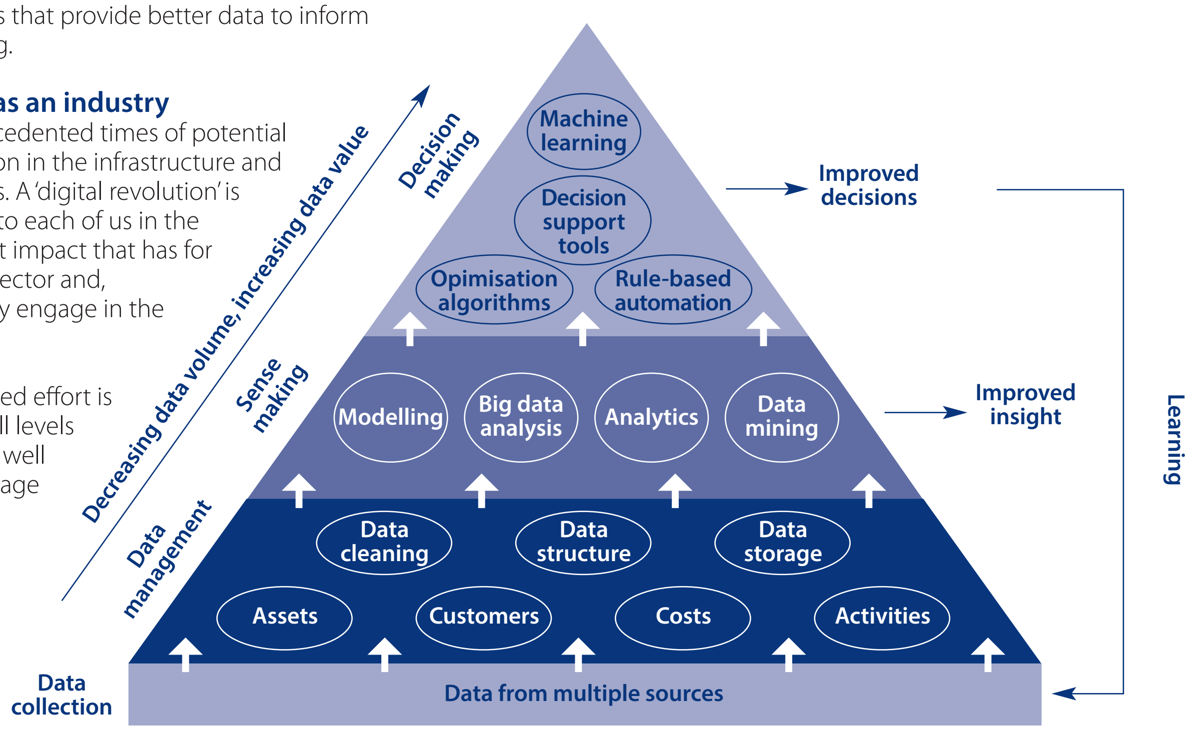


Figure 1: From big data to better decisions[1]

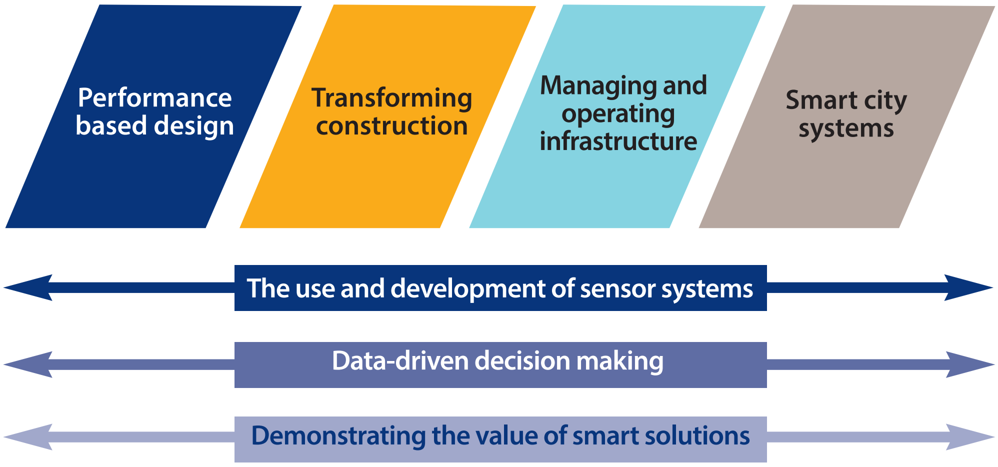


Figure 2: CSIC's strategic themes

Smart Infrastructure brings multiple benefits to all stakeholders: it will save significant amounts of money in effective asset management, improve the services and reliability delivered by our infrastructure and boost overall productivity of our economy.

Leading the change

CSIC's role as an Innovation and Knowledge Centre, rooted in academic excellence but collaborating strongly with industry, is to help lead and facilitate this change. We do this through translating research into practice and delivering outputs which industry can adopt. CSIC also engages strategically with policy makers, industry bodies and standards organisations to help create a marketplace for smart infrastructure solutions.

Providing integrated solutions

Moving forward, CSIC is now in a strong position to build upon its achievements over the past six years and consolidate a programme of collaborative activity based around enhancing the value of the entire life cycle of infrastructure, underpinned by sensing solutions, data analytics and decision tools, and value capture (Figure 2).

The last year has seen exciting developments with a number of monitoring projects yielding insights across these strategic themes. For example, the Leeds viaduct monitoring project (page 14), which evaluated the utility of a number of different monitoring solutions, developed an understanding of the structure and the response of the viaduct, and offered recommendations regarding potential operational and maintenance interventions. Taking a similar integrated approach to future projects will be important to supporting the uptake by industry of the outputs of CSIC and our academic and industry partners.

We are actively looking for opportunities to collaborate with partners across the supply chain to develop further integrated projects to deliver value and enable adoption in practice.

Supporting the Future City agenda

At the city scale, CSIC is launching an innovative project, funded by The Ove Arup Foundation, which will address the disciplinary gulf that currently exists between city managers, engineers and urban designers. It will catalyse and establish a significant ongoing research programme to address gaps and identify the digital tools required to deliver a smart city which benefits the citizens it serves. It will also create a competence framework for smart city professionals which draws together engineering and social sciences to deliver better outcomes for citizens.

Supporting the UK digital agenda

We have also been active in discussions with policy makers, standards bodies and professional institutions including the Department for Transport, the Digital Built Britain initiative, the Construction Leadership Council and the Institution of Civil Engineers, both informing and engaging in key activities around the digital agenda and helping to facilitate coordination in messaging and direction between these initiatives[2]. It is vital that the industry continues to engage with and support these plans, building on them to deliver a unified vision of a digitally enabled future.

CSIC will continue to engage strategically in this area, and will actively involve our partners in shaping and informing the future of infrastructure and construction.

Collaboration and innovation are key to optimising the opportunities that digital abundance brings. CSIC's strategy and partnerships will deliver benefits for all. Now is the time for industry and academia to work together to secure the best outcome for UK infrastructure.

[1] Adapted from Smart Infrastructure – Getting more from strategic assets, CSIC, October 2016.
[2] ICE State of the Nation 2017 – Digital Transformation; Digital Built Britain; Promoting Adoption of Smart Infrastructure Solutions in the Transport Sector – Recommendations to the Department for Transport Chief Scientific Advisor, CSIC, 2016; Construction Leadership Council Innovation (Buildings) group

Bojangles/Shutterstock

Digital transformation – achieving Smart Infrastructure

Mark Enzer
Group Technical Director
Mott MacDonald

The case for Smart Infrastructure

Conceptually, the case for Smart Infrastructure is very strong. In essence, integrated cyber/physical solutions offer a more cost-effective way of improving outcomes for ultimate customers than do traditional constructed solutions alone. The underlying driver for this assertion is that the unit cost of everything to do with data (harvesting it, transmitting it, processing it, and storing it) continues to reduce, whereas the cost of everything else keeps going up.

Relative to other industries, such as finance, retail or media, the infrastructure sector has been slow to benefit from digital transformation indicating that the case for Smart Infrastructure clearly still needs to be made. A key missing link in the business case is that the Infrastructure Industry generally considers value in terms of constructed output per capex pound making digital solutions look more like a cost than something of value. But as soon as we can see value in terms of outcome per whole-life pound, the proposition for Smart Infrastructure comes alive.

Our industry puts a value on physical assets, but not yet on digital assets. As the industry moves forward we must treat data as a resource and put a value on information in order to achieve a real digital economy – and an even stronger case for Smart Infrastructure.

Industry initiatives

With so much value on offer, it is not surprising that there are currently numerous industry initiatives relating to Smart Infrastructure, including:

- **Digital Built Britain** – driving the wider perspective of digital transformation across the whole Built Environment
- **Construction Leadership Council** – leading transformation across the construction industry; "getting more out of new and existing assets through the use of smart technologies"
- **Infrastructure Projects Authority** – developing the Infrastructure Performance Review, which focuses on whole-life performance
- **Engineering institutions** – driving thought leadership. The Institution of Civil Engineers recently published its State of the Nation report on digital transformation. The Institution of Engineering and Technology has led the thinking on smart energy networks
- **National Infrastructure Commission** – leading strategic thinking and analysis of the UK's long-term infrastructure needs, with a key focus on new technologies
- **Infrastructure Client Group** – driving digital transformation as part of Project 13, which seeks to transform the delivery of UK infrastructure from 'transactions to enterprises'.

Clearly it makes sense to bring these strands together in order to create a rope that pulls infrastructure in a smart direction. This is a key area in which CSIC is making a difference. Because its network is so extensive, CSIC has been invaluable in bringing thought leaders from industry and academia together. One significant example of this was the development of the Smart Infrastructure Paper[1] which outlines a simple framework for understanding Smart Infrastructure and presents its central value proposition in a bid to facilitate the industry adoption of 'smart'.

Smart alliances

More widely, academia has a huge interdisciplinary role in helping to achieve Smart Infrastructure. It is not just about driving innovation in new technologies or providing the skills that infrastructure needs – many of which are completely new to the industry. The infrastructure industry also needs social sciences to help it to understand inclusive social outcomes and it needs business schools and computer science labs to help with fundamentals like valuing data/information and developing new business models.

Collaboration has to be one of the keys for unlocking the value of Smart Infrastructure. When government, industry and academia pull in the same direction on this, the promised economic and social benefits will surely follow.

[1] Smart Infrastructure – Getting more from strategic assets, CSIC, October 2016.

The year in numbers

37 Innovation projects with industry

12 New grants awarded

£700K Industry in-kind funding

20 Phase 2 partners

26 Trade articles

£2M New funding

8420 Sensing points

31 Knowledge exchange events

25 Assets analysed

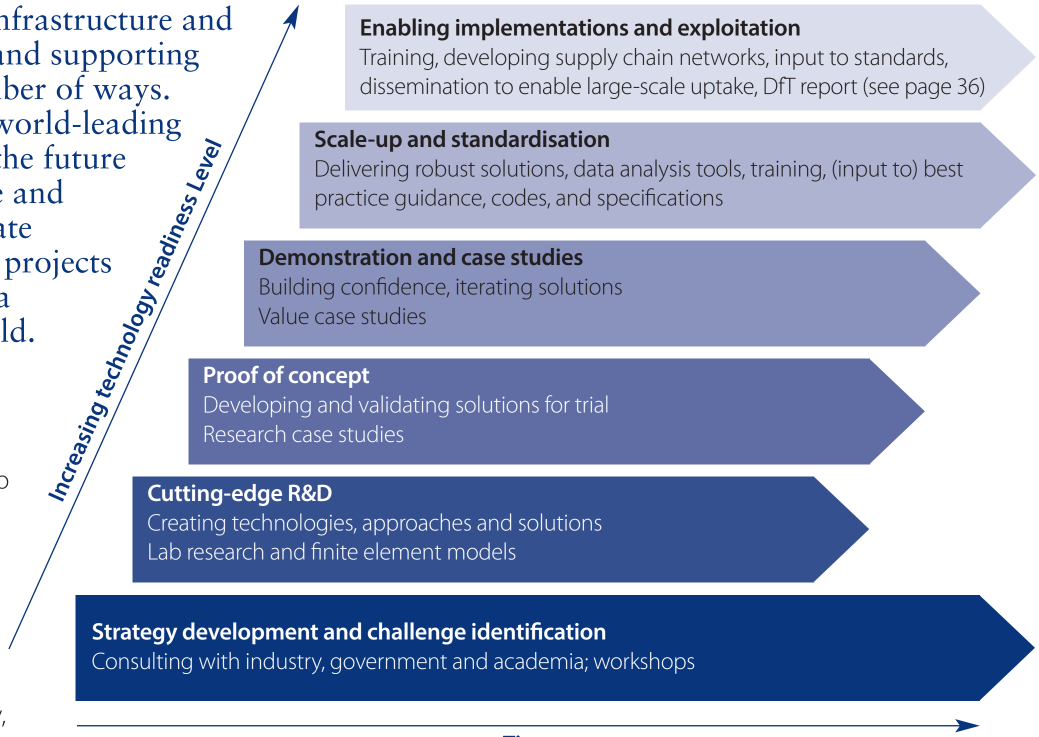
6 Cities modelled

12 Demonstrator projects

9 Direct engagements with businesses

Collaborate with us

CSIC works with the infrastructure and construction industry and supporting organisations in a number of ways. Our aim is to employ world-leading research to transform the future of Smart Infrastructure and construction, and initiate industry-collaboration projects to establish the UK as a global leader in this field.



CSIC's delivery model

Why work with CSIC?

The digital abundance that is shaping society brings opportunity and challenges to industry and responding in a timely and effective manner is key to success. CSIC is already working effectively at a number of scales across academic research, policy, standards and industry, and is uniquely positioned to integrate the skills, people and knowledge to enable industry to target wealth-generating opportunities and meet the challenges that come with transformative change.

Working with CSIC helps industry to optimise these opportunities by:

- being the first to learn about new technologies that can help companies to stay ahead of the competition
- undertaking high impact research projects with a trusted partner with unique capabilities
- implementing a strand of research to manage and reduce project risk.

Delivering effective solutions to industry

CSIC's Business Development and Knowledge Transfer team works closely with industry partners to identify and understand their key issues and challenges. CSIC then collaborates with these partners to research, design, develop and deliver effective and repeatable solutions.

Deployment

CSIC's vision is supported and shaped by our 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 deployment team is continually monitoring infrastructure, installing sensors, interpreting data, and implementing new procedures and protocols at a number of major sites around the UK.

Developing the value chain

CSIC is working to develop the value chain by collaborating with key technology suppliers to advance simplified and standardised installation. We are collaborating with industry partners to advance new instrumentation and sensors and new technologies that make sensors easier to install and more economical.

> "CSIC's network has introduced OptaSense to new clients, applying fibre optic DAS technology to industrially important pilot projects. CSIC has also facilitated links between OptaSense and academia, helping OptaSense to further its technology and IP base.

Jasbir Nagi
Senior Research Engineer, OptaSense
www.optasense.com

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, including specialist training courses, best practice guides and case studies.

Working with academia
CSIC actively seeks research partners from the UK and internationally. Examples of our academic collaborations include: Data-Centric Engineering with the Alan Turing Institute; WindAfrica with Durham University and the University of Pretoria in South Africa; Translucent Cities with the University of California, Berkeley and the National University of Singapore; and Behaviour of overhead line electrification foundations with the University of Southampton (see Research page 27).

The University of Cambridge is one of the founding members of UKCRIC (United Kingdom Collaboratorium for Research in Infrastructure and Cities)
UKCRIC has been established to enable the collaborative multidisciplinary research needed for the UK to retain and develop the physical infrastructure and engineered urban systems required to maintain world-leading intellectual and economic power in the 21st century and beyond. As part of a £138M capital investment by the UK government, the University of Cambridge has received £18.5M to establish the National Research Facility for Infrastructure Sensing (NRFIS), a new state-of-the-art research facility. This interdisciplinary collaborative hub will build upon the success of CSIC and focus on research in the application and development of advanced sensor technologies for monitoring the UK's existing and future infrastructure, in order to improve resilience and extract maximum whole-life value. NRFIS is due to open in summer 2019.

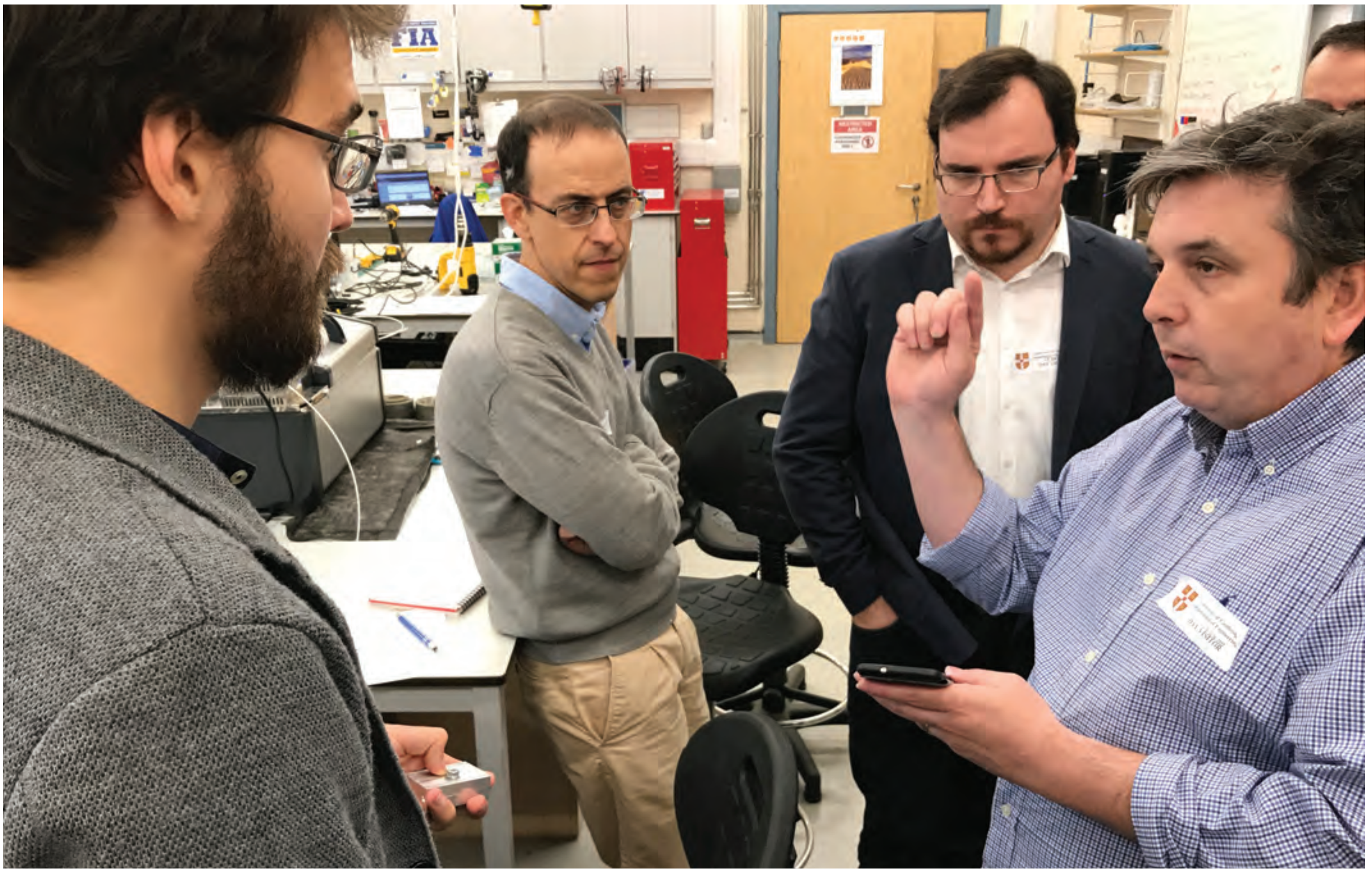
CSIC Partnerships – tailored for individuals and start-ups to multinational corporations
Partnership agreements enable collaboration and open engagement to help companies and organisations working in infrastructure and construction stay ahead of the game. By collaborating with partners, CSIC is able to accelerate implementation of research outputs, delivering value by improving margins, reducing costs, enhancing returns and extending the productive life of assets.

Other partnership benefits include the opportunity to second staff to CSIC to work closely with our R&D teams and to sponsor studentships at Masters and PhD level at CSIC and the University of Cambridge Department of Engineering. Additional benefits include support in the development of IP and the commercialisation of novel tools and technologies and access to CSIC training courses.

There are four types of partnership with varying levels of benefits: Full Partner, SME Partner, Micro Partner, and Associate Partner. Partnership collaborations lead to new skills and techniques that deliver smarter and repeatable solutions to industry challenges and provide case study evidence to highlight where significant savings and value can be made for the benefit of all stakeholders, cities and communities.

> “ CSIC has enabled us to form small and focused collaborative groups to work on specific problems within our industry, and with its support framework, we have been able to deliver an innovative new product from research stage to full commercialisation. This new and now patented product, CemOptics, produces significant safety, quality and commercial benefits for us and the wider industry. The innovation was delivered to market in an unusually short timescale and this accelerated development and delivery programme was made possible by the strong collaboration that exists within CSIC and the excellent support provided by the University of Cambridge.

Andrew Bell
Chief Engineer, Cementation Skanska
(See Integrity Testing case study on page 29)



“My secondment was for 12 months and I loved every minute of it. I forged links with industry and academia and these connections and relationships have already proved advantageous to Mott MacDonald, and will continue to be going forward.

Jules Birks
Chartered Engineer, Mott MacDonald

Collaborate – get in touch
Working with CSIC creates a symbiotic effect, amplifying the outcomes that derive from a strategic collaboration between academia, industry and policy. This in turn often leads to step changes in the commercial value of research, delivering greater efficiency in design and performance, a low-carbon society, sustainable urban planning and management and improved health and productivity.

To find out more about working with CSIC and the range of partnerships available contact:

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Business development
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CSIC installing a fibre optic sensing system onsite

Case studies

These case studies, implemented by CSIC in collaboration with its partners, demonstrate the value and benefit of Smart Infrastructure solutions across the lifetime of built assets, from design to construction and operational asset management. These are just five of the many projects that we have completed in the past six years. They represent solutions to challenges faced by industry on major infrastructure projects as well as less high profile engineering challenges, on both new and existing assets. Case studies like these provide evidence for the benefits of investment in Smart Infrastructure which is a key component of CSIC's mission to transform the future of infrastructure through smarter information.

1. Understanding the structural response of masonry arch bridges through sensing
2. Monitoring performance of reinforced concrete piles
3. Safety performance of timber structures in underground construction using wireless SmartPlank
4. Optimising the design of sprayed concrete linings
5. Monitoring confirms effect of deep diaphragm wall shafts on existing infrastructure

Understanding the structural response of masonry arch bridges through sensing

Benefit to
Asset managers and operators, designers

Impact and value
- better understanding of the response of masonry arch bridges
- more effective asset management and operation
- cost saving, time saving
- improved safety

Masonry arch bridges are an integral part of the UK's road, rail and waterway infrastructure. About 18,000[1] masonry arch bridges and culverts account for 47 per cent of Network Rail's total bridge population. These structures have shown themselves to be robust and reliable but many are now facing challenges due to age and modern use. Assessment of these structures often relies on visual inspection and engineering experience to establish when and where a bridge requires intervention. However, visual inspection is costly and time consuming and often does not reveal the underlying mechanism of damage. Understanding the behaviour of these bridges and development of cost effective assessment and maintenance systems will be key to securing their continued effective use. CSIC's masonry arch bridge research aims to quantify the vulnerability of these structures and provide detailed and accurate data that will better inform maintenance programmes and asset management.

Assessing the current state and long-term prognosis of a Victorian viaduct

Working with industry partner Network Rail, CSIC has been monitoring an operational Victorian masonry arch viaduct in Leeds for the past two years. The objective is to better understand the dynamic response of the viaduct to rail traffic and identify the mechanisms that drive its degradation. The bridge is visibly damaged due to water leakage and past settlements and there has already been maintenance intervention. A speed restriction has been in place on the rail line. CSIC assessed the effectiveness of the existing intervention and whether the damage is progressively getting worse due to temperature cycles and dynamic loads.

Deploying sensing technology

The dynamic response, measured while trains pass over the viaduct, was monitored on two adjacent spans of the viaduct using a Fibre Bragg Grating (FBG) sensing system. To our knowledge, this marked the first ever deployment of FBG sensors in a masonry viaduct worldwide. Evaluation of the resulting fibre strain data was made possible with a novel non-contact videogrammetry solution, provided by Imetrum. The results demonstrated excellent agreement and highlighted the ability of fibre optic cables to detect very small strains to illustrate the flow of forces inside the structure.

The monitored spans of the Victorian viaduct in Leeds

In addition, laser scanners were used to create a 3-D model of the underside of the arch to measure how the structure has deformed over time. The analysis of the deformed geometry from these models has enabled CSIC researchers to quantify the critical movements experienced by the structure in the past. An understanding of these movements has also helped develop a better understanding of the dynamic response of the viaduct to rail loads as it is also influenced by this existing damage.

What we found

Fibre optic sensing has provided a new understanding of how arches in the viaduct interact during dynamic rail loading. In particular, CSIC found that the rotation of the piers caused an opening in the span, and this action controlled how the arch responded to the dynamic loading. CSIC was also able to identify the critical sections of the structure which experience tensile forces and amplified compressive forces (e.g. due to crack opening or closing), where damage is likely to concentrate in the future.

Interestingly, the dynamic response was not found to be significantly affected by the speed of the train passing over this bridge, which operated at low speed. Further investigation may prove this to be the case at higher speeds and/or other bridge forms, providing an opportunity to modify Network Rail's response to emerging issues, reducing delays and negative effects to passenger experience.

This project has delivered a better understanding of the structural response of masonry viaducts. The sensing data has allowed CSIC to explain existing damage, to identify critical aspects of the structural response, and to better evaluate the effectiveness of potential intervention techniques.

Next steps

CSIC researchers are now applying the understanding of the response of this particular bridge to other similar viaducts. New assessment techniques are being formulated and measurements in similar viaducts are being recorded for this purpose. CSIC researchers also plan to further explore critical engineering issues, including the degradation of existing damage and the influence of increasing train speed and angle of bridge skew on the dynamic response of masonry arch bridges.

An arch instrumented with FBG cables and photogrammetry targets in the viaduct

Imetrum videogrammetry camera

> CSIC's deployment of fibre optic sensing to monitor this masonry arch bridge has provided new insights into the behaviour of this type of structure which could lead to improved assessment and management procedures.

Mark Norman
Route Programme Manager, Network Rail

[1] Orbán, Z. (2004). Assessment, reliability and maintenance of masonry arch railway bridges in Europe. *Arch Bridges IV–Advances in Assessment, Structural Design and Construction*. Eds: P. Roca and C. Molins, Barcelona, 2004, 152-161.

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Monitoring performance of reinforced concrete piles

Benefit to
Designers, piling contractors

Impact and value
- cost-effective
- provides multi-metric distributed monitoring
- enables better understanding of performance of as-built pile

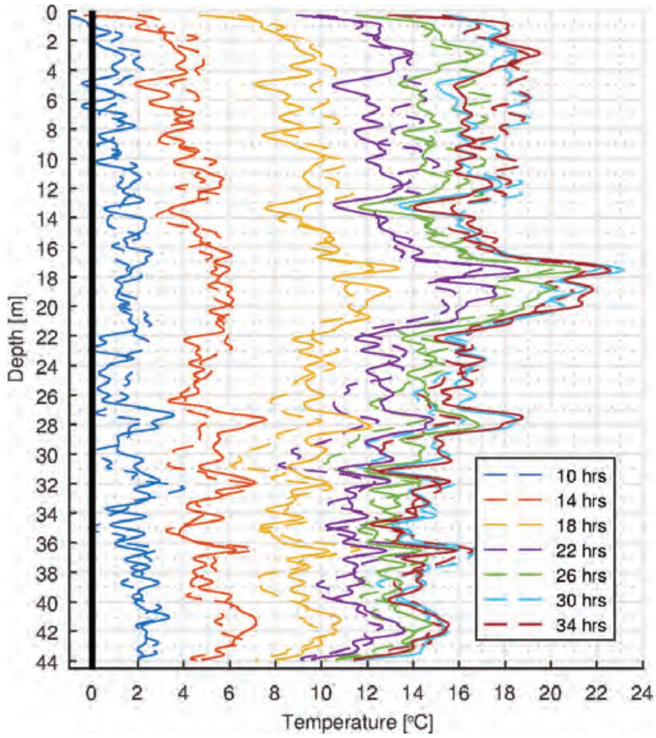

Figure 1a

Figure 1. Profiles of (1a) concrete curing temperature, (1b) load test strain and (1c) load test displacement obtained from two opposite sides (solid lines and dashed lines) of a test pile monitored with DFOS.

Distributed fibre optic sensing for pile monitoring

Traditionally strain gauges and extensometers have been used to monitor reinforced concrete piles. However, the information that they can provide is limited as they only return measurements at discrete points rather than along the entire length of the pile. The University of Cambridge and CSIC have been developing distributed fibre optic sensor (DFOS) systems for monitoring different types of infrastructure over the past 10 years. DFOS is ideal for monitoring strain or temperature over distance or area, and particularly useful for detecting phenomena such as cracks, material anomalies or embedded defects that cannot be observed with point sensors.

The advantages of monitoring piles with DFOS is that, with a single instrumentation, one can measure the concrete curing temperature as well as strain and displacement during pile testing or during the operational phase of a working pile. DFOS provides a complete profile along several sides and down the entire depth of the pile, thus delivering more information than strain gauges or extensometers that provide measurements only at single points.

Better smarter monitoring

Figure 1a demonstrates the importance of obtaining a continuous measurement profile along the whole depth of a pile – an advantage of using DFOS. Here, data from a compression test pile show the concrete curing temperature at regular intervals. The concrete reached peak temperature after about 34 hours. Normally the temperature profile would be fairly uniform along the whole depth. However, in this case, there is a clear rise in peak temperature at about 17m depth. This is indicative of an anomaly; for example a larger pile diameter due to a localised overbreak, or a soil inclusion or air void that is preventing the heat of hydration from dissipating. This pile was also tested with cross-hole sonic logging by an independent contractor, which confirmed the presence of an anomaly at the same location.

The pile was then tested using a standard static load test. The strain profile was plotted for every load step and a very distinctive spike in compressive strain was observed at the location of the suspected anomaly, mainly on one side of the pile, confirming the presence of a very localised weak spot in the pile (Figure 1b). This information could not have been acquired by an embedded vibrating wire strain gauge. Even if there was a gauge at this exact location, it is likely the gauge would be thought to be faulty and its readings ignored. An added bonus to the continuous strain profile is the ability to obtain a profile of the pile's displacement with depth, relative to the pile head, with an accuracy of around a tenth of a millimetre (Figure 1c).

> "We have used DFOS provided by CSIC for both thermal integrity testing and instrumenting preliminary test piles. For both purposes, DFOS has been extremely valuable in confirming and correcting the data from traditional instrumentation. However, the real difference with DFOS is the provision of a continuous profile of data down the full pile length, not just at discrete locations. This is something traditional instrumentation just cannot do.

Stuart Hardy
Associate Director, Geotechnical Engineer, Arup

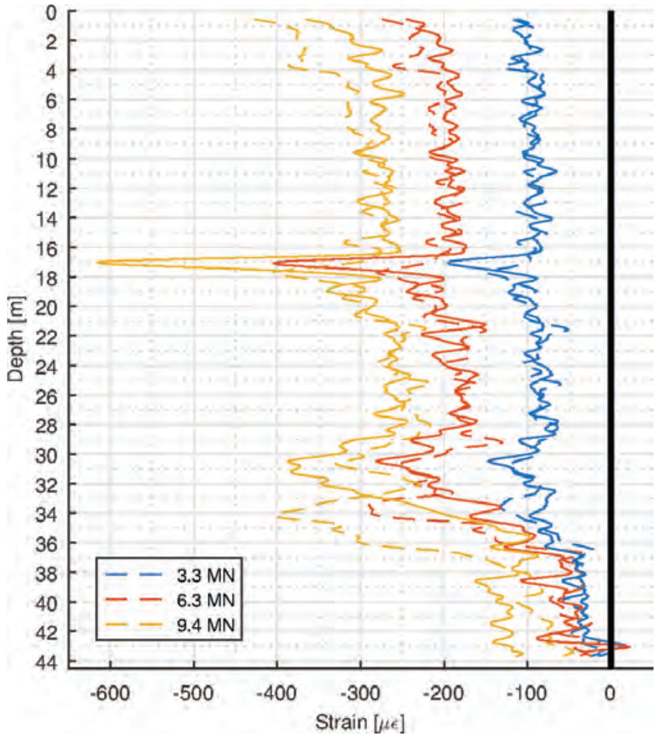

Figure 1b

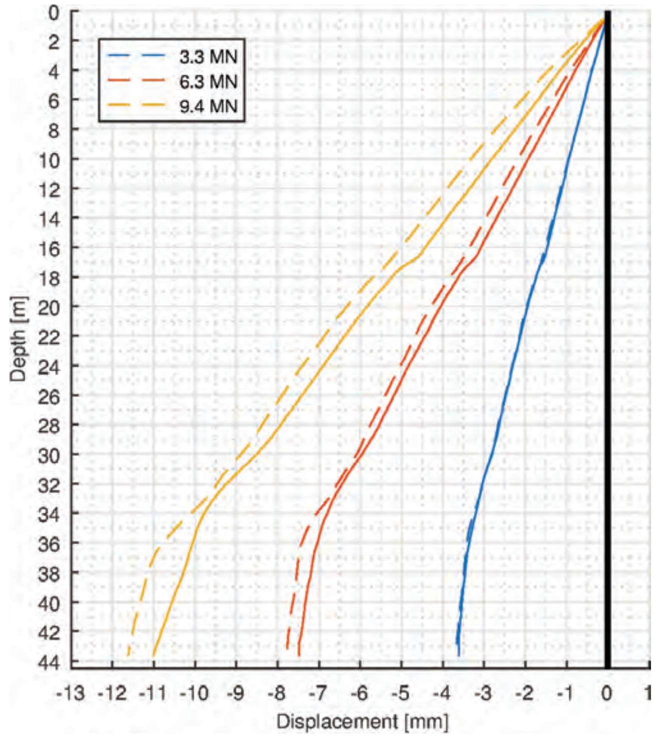

Figure 1c

Industry ready

After many field trials and incremental improvements, CSIC has developed the capability and processes to enable fast and easy installation of DFOS, which has led to rapid industry uptake in the past two years. DFOS monitoring is now specified in the 3rd edition of the *ICE Specification for piling and embedded retaining walls* (SPERW) [1] which CSIC contributed to. Following initial training on site by CSIC, the fibre optic cables can be installed by the piling contractor's operatives under the supervision of CSIC specialists. The cables are attached along the length of the pile cage, on two or more sides, and can also be installed on central rebar bundles. Monitoring can start from the moment the cage is inserted into the pile bore to be concreted. DFOS can be used to monitor sacrificial test piles or working piles, comprising one or more cages. It has been used in bored piles and continuous flight auger (CFA) piles, and in both tension and compression piles. CSIC provides DFOS pile monitoring as a commercial service in partnership with the spinout company, Epsimon Ltd. In the past year, the CSIC/Epsimon partnership has carried out pile monitoring projects at a number of major construction sites in London.

Cost effective

Since DFOS enables many measurement points per metre of cable, it is a cost effective technology for pile monitoring as the equivalent cost per sensing point is very low compared with traditional point measurement sensors. Most of the capital investment relates to the optical spectrum analyser, which can be used to monitor several piles simultaneously, or be shared across different sites. However, in the vast majority of projects it is the monitoring service provider, such as CSIC/Epsimon, that owns the analyser and provides it as part of the service, thus reducing the cost of the monitoring project significantly.

[1] ICE Specification for piling and embedded retaining walls, Third Edition, ICE Publishing, 2017. ISBN 9780-0-7277-6157-6

An instrumented CFA pile cage being inserted into the pile bore

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Safety performance of timber structures in underground construction using wireless SmartPlank

Benefit to
Designers, contractors

Impact and value
- construction safety
- optimised design

Use of timber in underground construction

Although timber structures have been used extensively in underground temporary supporting systems, their actual performance is poorly understood, resulting in potentially conservative and over-engineered design which presents a manual handling risk to site operatives. A novel wireless sensor technology, SmartPlank[1] , has now been trialled on two projects – a short trial at London Underground's Victoria station and a two-year trial at Tottenham Court Road underground station – to monitor the field performance of temporaty timber structures during underground construction. Through a better understanding of performance, design of these structures can be optimised and risk of injury to workers can be reduced.

Monitoring timber performance with SmartPlank

A typical installation of SmartPlank consists of horizontal head planks supported by vertical side planks using Yankee brob (steel to hold face timbers) (Figure 1). The top plank takes bending load while the side planks hold the vertical load axially and the lateral bending load. With this layout, strain gauges and temperature sensors are attached on both the top and bottom surfaces of the timber plank and a wireless sensor node is attached to the underside. The top plank is countersunk by having the side planks shortened to accommodate the sensors, which enables a constant height for all timber frames. The engineering information measured by SmartPlank is wirelessly transmitted in real-time while the underground construction is taking place.

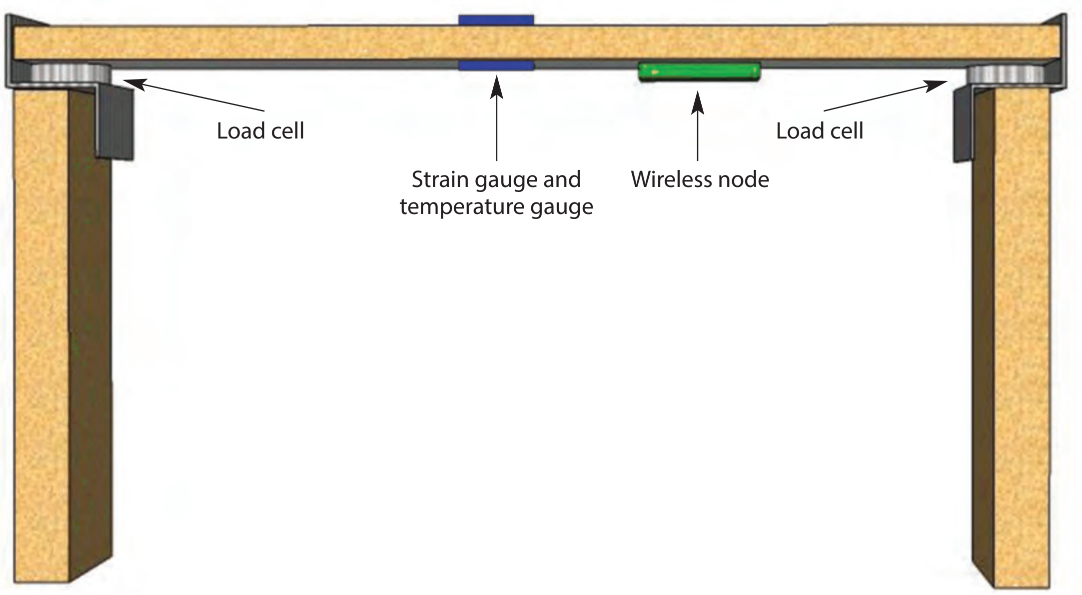
SmartPlank deployment at Tottenham Court Road

Over the past several years, London Underground's Tottenham Court Road (TCR) station has been upgraded to meet the expected rise in passenger numbers interchanging between London Underground services and Crossrail in 2018. One sub-project is to provide a new access from Stair 14 to the Central Line platforms to reduce congestion. Temporary works were installed from the Stair 14 upper landing in order to create space for construction activities. Reinforced concrete and steel frames together with timber were employed to support the ground following excavation.

Four SmartPlanks numbered as SP51, SP52, SP53 and SP54 were deployed at Stair 14, each with a rectangular cross-section of 200mm×100mm. A strain gauge and a temperature sensor and wireless sensor node were attached to each plank. Each SmartPlank was then tested to check its connectivity, and to take the baseline readings prior to installation. The instrumented SmartPlanks were then wrapped with tape to protect them from any physical damage.

The SmartPlanks were installed together with the other timber planks and were switched on immediately after installation. Grouting was then carried out immediately after the timber heading at each stage, to prevent softening and loss of ground. The grout also acts as a seal to prevent the clay being exposed to the air in the tunnel. Two other steel bearings were then added to the middle a week after the plank installation. Figure 2 gives a picture of SP52 installed at Stair 14 TCR.

Figure 1. Idealised SmartPlank prototype



[1] Performance monitoring of timber structures in underground construction using wireless SmartPlank. Xu, X., Soga, K., Sarfraz, N., Moss, N., Bowers, K. and Gajia, M. Smart Structures and Systems. Vol. 15, No. 3 (2015) 769-785.

Wireless sensor network at TCR

A wireless monitoring network was formed to monitor the field performance of the SmartPlanks. The monitoring frequency was automatically set in the software to take a set of readings every 15 minutes for the first week, and then take hourly readings afterwards. Monitoring of the SmartPlanks continued for two years from installation.

Understanding the performance of timber structures in underground construction

Results from the SmartPlanks indicate that the short-term performance of the planks was governed by the grouting process, which is not considered as part of the short-term earth pressure design. The grouting effect may be minimised by reducing the grouting pressure, or strengthening the support before grouting. For the long-term earth pressure, the normalised pressures deduced from the strain data of SP52 and SP53 were between 3 per cent and 8 per cent, which are much smaller than the design value of 40 per cent. Normalised pressure is the deduced earth pressure divided by the total earth pressure at the relevant depth.

The SmartPlanks continued to deform over a period of 10 months after their installation. The deforming process can be divided into two stages: from 1 month to 3 months and after 3 months. For SP52, the strain change at the first stage was around 4.7 times faster than that of the second stage.

Supporting studies

As well as the field tests, SmartPlank was also tested in the lab at the Department of Engineering at the University of Cambridge to understand if the way the strain gauges were installed affected the results. Additionally, a numerical modelling study of SmartPlank was undertaken and compared to the field test results. The performance of SmartPlank in the lab and the numerical model was found to be similar to the field tests.

Next steps

Monitoring of temporary timber structures with SmartPlank has provided a better understanding of the performance of these structures. With additional field tests, this new understanding can lead to optimised design and improved safety for construction workers.

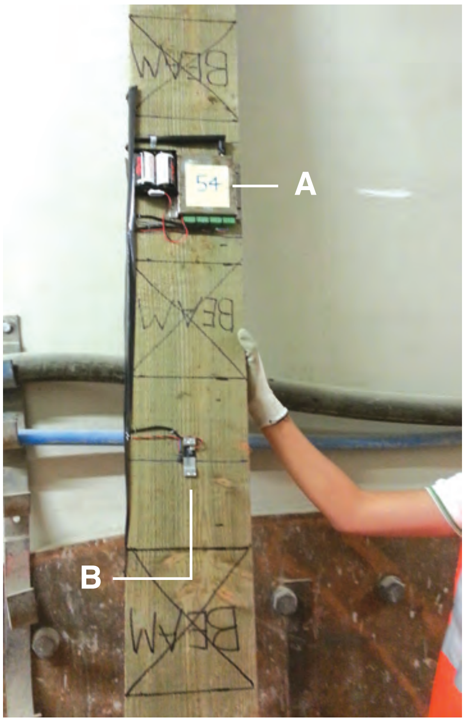


Figure 2. Instrumented SmartPlank (A = wireless node, B= strain gauge and temperature sensor)

Figure 3. Deployed SmartPlank at TCR Stair 14. (A = wireless node, B= strain gauge and temperature sensor)

“ Monitoring of temporary timber structures with SmartPlank has provided a better understanding of the performance of these structures. With additional field tests, this new understanding can lead to optimised design and improved safety for construction workers.

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Optimising the design of sprayed concrete linings

Benefit to
Designers, contractors

Impact and value
- validation of design
- cost saving, time saving
- construction safety
- sustainability

This innovative project presented an opportunity for CSIC to collaborate with industry partners Crossrail and Mott MacDonald to use fibre optic cables to observe and monitor the behaviour of sprayed concrete linings (SCL), a technique used to construct the station tunnels on the Crossrail project. The results demonstrate how a distributed fibre optic sensor (DFOS) system can be an effective tool for understanding the structural behavior of SCL, which leads to a better understanding of key design parameters to inform and improve future SCL design.

SCL at Liverpool Street station

The project aimed to gather data on the behaviour of SCL during breakout and excavation of the cross passage junctions in the tunnels at Liverpool Street station. The goal was to produce reliable field data to investigate the accuracy of the 3D finite element models used to design the cross-passage junctions. In particular, the response of the reinforced thickening layer of SCL added at the tunnel enlargement chambers at cross-passage junctions was investigated with the aim of finding new techniques to save time and money.

DFOS installation

CSIC embedded a DFOS system within the thickened SCL in enlargement chamber CH5 (Figure 1) at two cross-passage junctions, CP1 and CP2 (Figure 2), in order to monitor the changes in the continuous strain profile that occurred in the tunnel lining during the excavation. The distributed nature of the strain measurements obtained from the DFOS system made it possible to reconstruct the strain map in the tunnel lining during every stage of the cross-passage excavations, with unrivalled spatial detail. This information was used to compare the predicted structural behaviour obtained from the finite-element models with the true performance of the tunnel lining.

Understanding SCL performance with smart data

Data collected indicated that the load redistribution within the tunnel SCL during the cross-passage excavation was localised and significant increases in strain were limited to a relatively small distance from the cross-passage openings (1 - 2m). This is considerably smaller than the extent of the thickening SCL. These findings suggest that the benefit of the thickening SCL layer diminishes rapidly with increasing horizontal distance from the cross-passage openings and is unlikely to be necessary beyond the first 3m either side of the openings. This is an important finding because it implies that the tunnel enlargement chambers at cross-passage locations could be reduced in length, leading to safer construction and considerable savings in construction time and cost.

Better design, cost savings, and increased safety through DFOS monitoring

While further research is needed, the results of this investigation indicate significant savings could be made in future designs. Extrapolating the results to the six cross-passage pairs, with three junctions per pair (one for each tunnel) at Liverpool Street, and across the 10 new Crossrail stations, similar projects could potentially save millions of pounds in project costs with the additional benefits of improved safety, reduced carbon emissions and shorter construction times. Similar studies to confirm these findings could result in real savings for comparable projects such as Crossrail 2 and HS2.

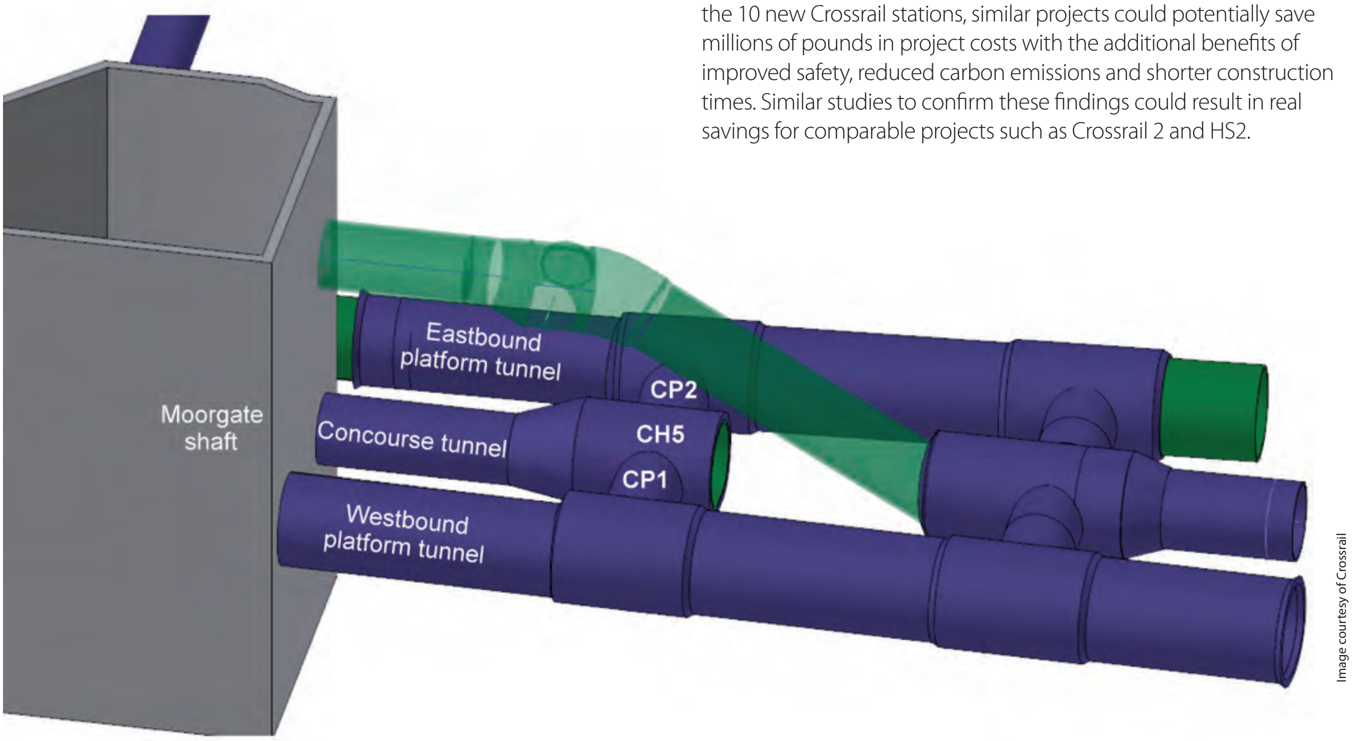

Figure 1. Model of the western end of Liverpool Street station and enlargement chamber CH5

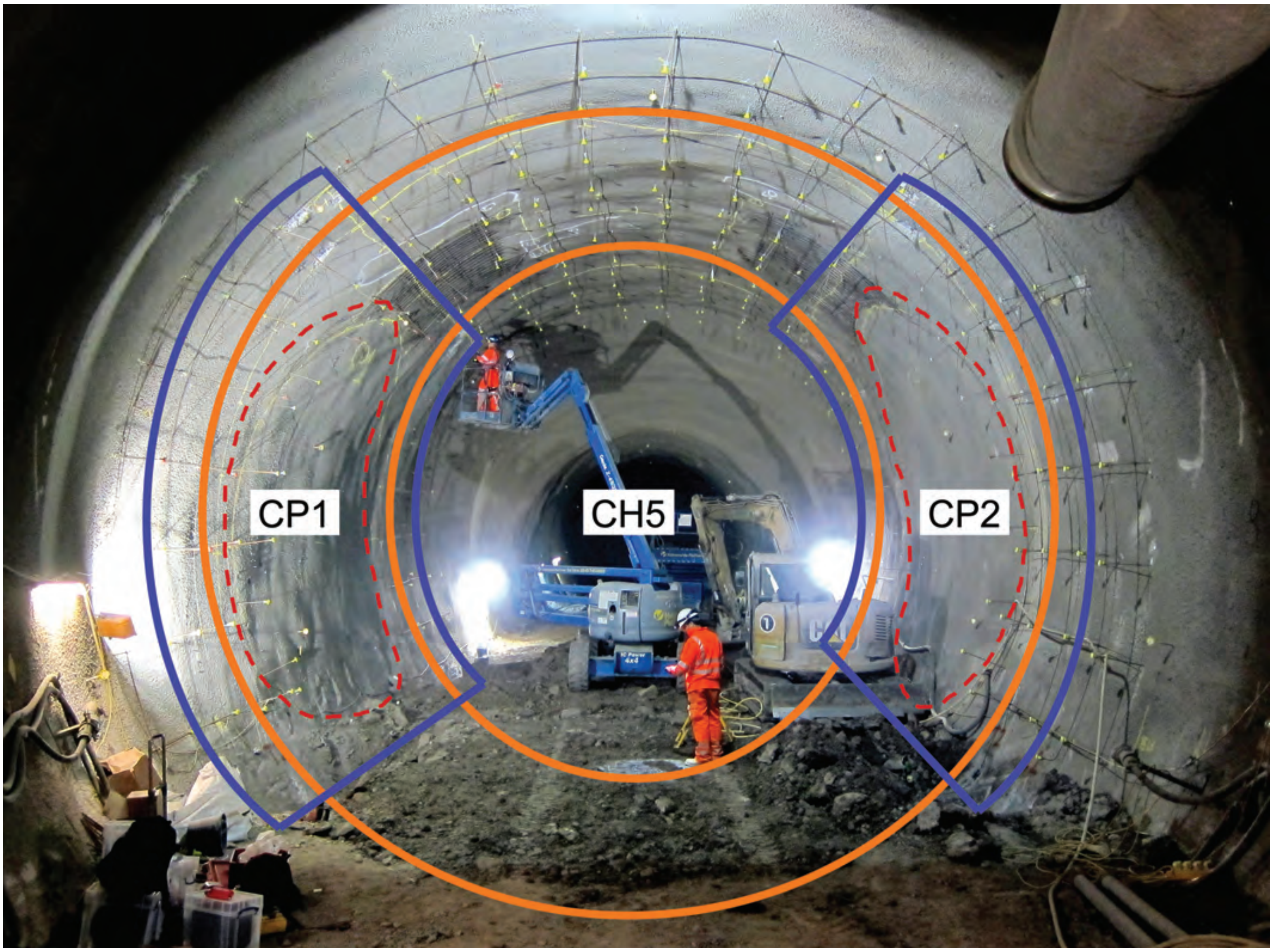

Figure 2. Enlargement chamber CH5 with DFOS circuits within the SCL at cross passages CP1 and CP2: two rings (orange) and two rectangles (blue)

> CSIC's work on Crossrail and other related projects is cutting edge. Optic fibre strain gauges were used to measure the performance of our tunnel sections and shafts – something that is a first anywhere in the world. These projects are being developed for us to better understand how our structures and assets behave and how, long term, we can save money through more economic design and reduced life cycle costs.

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Monitoring confirms effect of deep diaphragm wall shafts on existing infrastructure

Benefit to
Designers, contractors, asset owners

Impact and value
- reduced mitigation costs
- optimised design

Understanding the behaviour of circular diaphragm wall shafts

Circular diaphragm wall shafts are commonly used in tunnelling projects for ventilation and access, but there was limited knowledge on some aspects of the structural performance of the lining in these shafts; in particular, the development of circumferential hoop stresses in the lining had not been well understood. In addition, due to a lack of empirical data and relevant case studies for these structures, designers have taken a conservative approach to estimating ground movements associated with construction, resulting in larger predictions than would probably occur in practice. Conservative designs result in higher costs and expensive structures.

Abbey Mills Shaft F

The construction of Thames Water's Abbey Mills Shaft F in East London between 2011 - 2013 provided a unique opportunity for CSIC and partners Thames Water, MVB JV, AECOM, CH2M HILL, Bachy Soletanche and UNPS, to implement an unprecedented large-scale monitoring scheme to assess the shaft lining structural response as well as ground movements associated with the construction of deep diaphragm wall shafts. With a depth of more than 70m and a diameter of 30m, Abbey Mills Shaft F is one of the largest shafts ever built in soft ground conditions in the UK. The shaft had to pass through mixed and challenging ground conditions including made ground, alluvium, river terrace deposits, London Clay, Lambeth Group, Thanet Sand and chalk. This major engineering scheme forms an integral part of the Lee Tunnel and Thames Tideway Tunnel projects, helping to stop sewer overflow and improve water quality in the River Thames.

Image courtesy of Thames Water

Deep circular diaphragm wall shaft – monitored with fibre optic instrumentation

Image courtesy of Thames Water

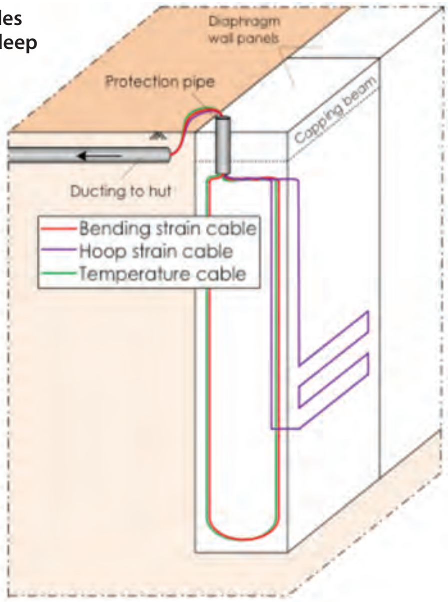
Installation of reinforcement cage with fibre optic cables

[1] Schwamb T, Soga K, Mair RJ et al. (2014) Fibre optic monitoring of a deep circular excavation. Proceedings of the Institution of Civil Engineers – Geotechnical Engineering 167(2): 144–154.
[2] Schwamb T, Elshafie M, Soga K, Mair RJ (2016) Considerations for monitoring of deep circular excavations. Proceedings of the Institution of Civil Engineers – Geotechnical Engineering Vol 169 Issue GE6, pp.477-493.
[3] New BM and Bowers KH (1994) Ground movement model validation at the Heathrow Express trial tunnel. In Tunnelling '94. Springer, Dordrecht, the Netherlands, pp. 301–329.

Monitoring with fibre optic and conventional instrumentation

Monitoring at Abbey Mills Shaft F included both fibre optic (FO) and conventional instrumentation.

Figure 1: FO cables installed in the deep diaphragm wall panels



***Fibre optic monitoring*[1]**

FO cables were installed in three of the twenty 1.2m thick and 84m deep diaphragm wall panels that made up the primary lining of the shaft (Figure 1). The panel reinforcement cage was instrumented with three FO cables to measure bending strain along the entire depth of the wall as well as hoop strain at predefined locations. This marked the first use of fibre optics to measure bending and hoop response in a deep underground diaphragm wall.

Installation involved two stages: (1) a pre-installation on the first reinforcement cages for each panel when the cages were still lying on the ground; and (2) the main installation when the remaining cages were lifted into position, welded to the cages underneath before being lowered into the bentonite-filled trench. Baseline readings were taken before and during shaft excavation until the final excavation depth was reached. The installation was part of a live project so CSIC had to ensure only minimal disruption to the construction process. The results were compared to predictions obtained from a finite-element model of the shaft using the Plaxis software package.

***Conventional monitoring*[2]**

Conventional monitoring was used to measure wall and ground movements associated with the shaft excavation. Instrumentation included manual inclinometers (lateral movement), multi-point automatic rod extensometers (vertical movement) and magnet extensometers installed in boreholes in the surrounding ground, as well as surface levelling pins. In addition, manual inclinometers were installed in the diaphragm walls of the shaft to measure wall deflections. Interpreting measurements from inclinometers is known to be challenging and CSIC took steps to correct accumulated errors. The ground movement measurements were compared to an existing empirical method proposed by New and Bowers (1994)[3] to validate its applicability to deep diaphragm wall shaft excavation. The wall movements were compared to numerical predictions obtained from a numerical parametric study using FLAC2D software.

Key findings

The monitoring of Abbey Mills Shaft F provides new information that has implications for the future design of deep circular excavations:

- inclinometer/extensometer data showed very small wall movement (maximum deflection of 4mm) at the final shaft excavation depth which is in good agreement with numerical calculations
- the overall ground settlement was very small - max 8mm settlement during wall construction, and heave of about 5-10mm likely during excavation. In contrast, empirical predictions of settlement were up to 40mm
- FO measurements showed that the overall radial movement of the diaphragm wall was very small. During excavation the measured hoop and bending strains of the wall, principally in the chalk, exceeded the predictions. This may have been caused by non-verticality of the walls and/or the structure may be less stiff than assumed in design due to decreasing effective wall thickness with depth.

Monitoring delivers cost savings and assurance

As a result of ground movements being considerably less than the design predictions, an estimated cost saving of at least £10 million in risk mitigation will be saved for future Thames Water construction projects.

Additionally, monitoring has provided a better understanding of deep circular shafts and diaphragm wall shafts to improve future design to save time, materials and money, ultimately delivering a more sustainable and affordable structure.

This project won the Fleming Award 2013 from the Institution of Civil Engineers

> “ The confirmation of the design models that will be realised by this work will give greater confidence and fewer objections by third party structure owners and operators thus reducing the level of institutional objection during the planning process.
>
> **John Greenwood**
> **Tideway Tunnels, 2013**

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Keeping cities moving through integrating smart solutions

Urban transport networks are under great strain from rising travel demand in areas of rapid population increase. For cities with established transport networks, strict emissions targets and limited physical space for development, it is no longer economically viable or sustainable to deal with increased demand by simply adding new capacity. These case studies show how CSIC's research – from complex city-scale systems and operations to individual assets –combine to deliver integrated smart solutions for the design and management of UK infrastructure.

Understanding travel behaviour in the age of big data

Tim Hillel, Doctoral Researcher

Managing travel demand directly by combining network improvements with policy and regulatory changes, including new scheduling and pricing schemes which encourage passengers to adapt their travel behaviour, brings benefits to operators. This new approach necessitates a significantly deeper understanding of the seemingly random variations of passenger flows. The recent adoption of several notable technologies, including contactless payment cards, mobile phone-based location services, vehicle tracking cameras, and connected vehicles has enabled a step-change in the availability of passenger movement data. Using London as a case study, this project is deploying machine learning techniques to infer causal relationships between network conditions and passenger transport decisions. This is achieved using an iterative loop between deep learning as a pathfinder, and structured, consumer utility-based travel behaviour models as verification. This enables a novel perspective in understanding how people interact with transport services and the wider urban environment, and establishes a new paradigm in travel behaviour modelling in the age of big data.

Using new sensing technology to understand the complex structural response of masonry arch bridges

Dr Sinan Açıkgöz, Research Associate

Dr Matthew DeJong, Senior Lecturer in Structural Engineering

Working with Industry Partner Network Rail, CSIC monitored an operational Victorian viaduct in Leeds, one of around 40,000 masonry arch bridges that form an integral part of the UK's road, rail and waterway infrastructure. The objective was to better understand the dynamic response of the viaduct to rail traffic and identify the mechanisms that drive its degradation, to inform maintenance and long-term management. The research has provided new insights into the behaviour of this type of ageing structure and the potential for a more accurate condition assessment. The sensing data has provided an explanation of existing damage, identification of critical aspects of the structural response, and better evaluation of the effectiveness of potential intervention techniques.

Harvesting spatially and temporally dynamic data on travellers

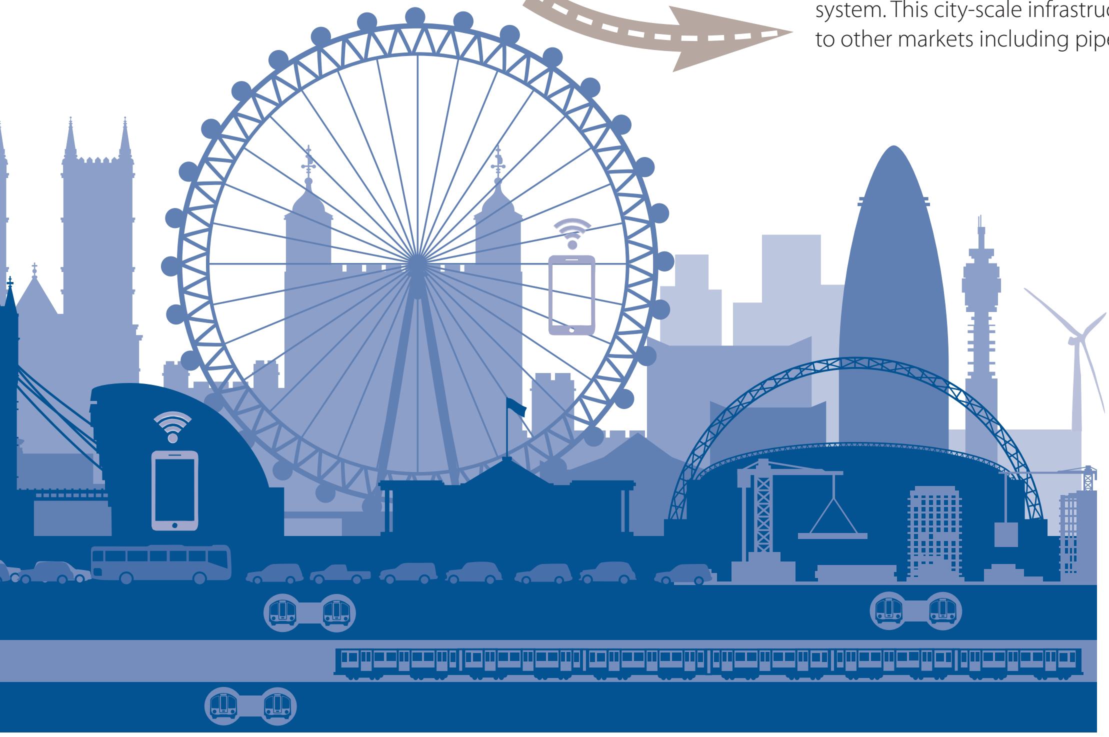
Gerard Casey, Doctoral Researcher

Historically, transport planners have made use of top-down macro-economic models that treat transport modes as distinct using models informed by static averaged inputs from standardised functions or limited survey data. Computational advances that enable complex, bottom-up fine resolution simulations to be carried out over long time frames, plus the emerging network of geospatially-connected devices, enables the harvesting of fine resolution spatial and temporal data on travellers. Even infrastructure itself permits crowd-sourced data to be used to inform dynamic models with real-world and real-time data. This step-change bypasses the need for generalised functions and/or expensive survey data and informs a framework which consists of a multi-modal agent based model (ABM) that can be used for a range of scenario testing exercises, including hard infrastructure and/or policy changes. The ABM facilitates scaling and makes use of a large repository of spatially and temporally dynamic data in order to provide real-world inputs. It also allows for the macro and micro impacts of changes to be assessed. This novel framework offers a wide range of valuable applications including, for example, how high speed rail usage has evolved in the case of HS1 in the UK and what implications this has for low carbon international travel in this region of Europe.

City-scale infrastructure simulation

Bingyu Zhao, Doctoral Researcher

Traditional degradation models for transport infrastructure focus on the behaviour of discrete elements of a transport network – a single road or railway section – which limits the development of more efficient network-level maintenance plans. New systems-based models are required to increase the efficiency of maintenance programmes and reduce costs. A novel, cell-based system-level infrastructure degradation and maintenance simulation model that interacts with the current abundance of digital information available for infrastructure networks is in development. This new model proposes upscaling traffic infrastructure degradation models to a system (city) scale to enable asset managers to make better-informed network maintenance decisions which are optimised for the whole system. This city-scale model uses extensive data obtained from automated surveys covering large spatial scale and many types of structures. It operates on a multimodal transport system and includes condition-influencing factors such as traffic, climate and geotechnical properties. The model symbiotically connects infrastructure to the people using it; more people results in further degradation which may also affect people's usage of the infrastructure, as well as fuel consumption and emission. Potential benefits from a city-scale model include more effective and efficient use of maintenance budgets and an improved public transport system. This city-scale infrastructure system could potentially transfer to other markets including pipelines and electricity grids.



Predictive maintenance of bridges

Zhenglin Liang, Research Associate

Complex industrial assets such as bridges, power transformers etc., are subject to complex deterioration processes. Understanding such complexities and maintaining such assets is a major challenge. This research has designed a novel approach for optimising condition-based maintenance policies for assets with complex deterioration processes. These policies aim to optimise the inspection and replacement plans for such assets and their constituent components so as to minimise the costs and risks involved, while maintaining performance. Working with a local authority, CSIC assessed the effectiveness of the approach on a road bridge system. At the bridge level, detailed deterioration models were formulated for different components of bridges under different exposure levels. At the system level, the economic dependence and two different levels of structure dependence are considered. The timing of maintenance activities is then optimised for the system based on current predictions for both risk and cost, with a goal of reducing the traffic management cost by combining maintenance activities. The result shows that our developed approach has the potential to reduce the maintenance cost by as much as 10 per cent by using this structural asset management planning toolkit.

Wind power in Africa
CSIC's WindAfrica project seeks to improve the foundation design for wind turbines in developing countries

Pieterjan Groble/Flickr

Research

CSIC continues to innovate at the cutting edge of research and in application. The following projects illustrate some of the wide ranging research that CSIC is currently involved with from developing novel sensors and their applications through to revolutionising the development of renewable energy in developing countries and reimagining our cities.

1 Measuring axial shortening
of a high-rise building using distributed fibre optic sensing

2 Integrity testing
of deep foundations using fibre optic methods

3 Optimising design costs
of overhead line electrification foundations

4 Settlement monitoring of heritage structures
Part of the Bank Station Capacity Upgrade – St Mary Abchurch and Mansion House

5 Translucent City
Transforming the use of undergound space

6 Transitioning cities
Enabling the evolution of smart cities

7 WindAfrica
Improving foundation design for wind turbines in developing countries

8 Mixed reality
for automated solutions for construction progress monitoring

9 Bridge inspector
An automated approach to help prioritise bridge inspection programmes

10 Data-driven asset management
A framework for linking ISO and BIM standards for whole-life value

11 Tram vibration and impact monitoring
Lowering maintenance costs and improving public acceptance

Measuring axial shortening

of a high-rise building using distributed fibre optic sensing

Project 1

Benefit to
Designers, contractors

Impact and value
- assurance that design assumptions are correct
- greater understanding of built asset and construction techniques

CSIC has been developing distributed fibre optic sensors (DFOS) in a range of civil applications over a number of years. This project involves a novel commercial application of DFOS to continuously measure the progressive axial deformation of reinforced concrete columns and walls. It is being trialled for the first time in the 50-storey Principal Tower throughout the building's 17-month construction programme. The axial shortening data provided allows the contractor to adjust the column height presets in the reinforced concrete structure if necessary. No other monitoring technology is able to provide this information.

This is a new collaborative approach to fibre optic (FO) instrumentation where the installation is carried out by the contractor's operatives trained by CSIC's specialists, while CSIC analyses the data and provides the required information to the contractors, Multiplex Construction Europe Ltd and Careys. The system provides important information to the contractors and design engineers (WSP Group) which they can use to ensure that the construction is proceeding as expected and to assess the accuracy of design predictions.

Temperature and strain sensing fibre optic cables are embedded in vertical load-bearing concrete elements, in four locations, as the building is constructed level by level. The tower is being constructed using an automated jumpform that incorporates the whole building footprint, including the columns. It is the first building in the UK to be constructed using this type of jumpform. The FO cables are housed in reels within the jumpform rig and are unwound and embedded within the concrete as the construction progresses upwards.

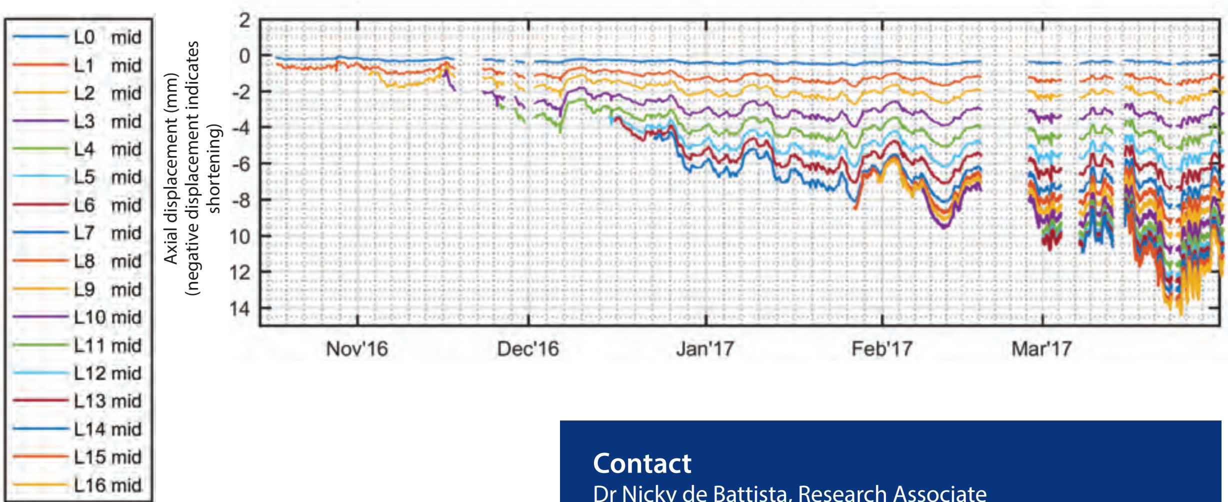
The DFOS system provides approximately 3000 sensing points along the fibre optic cables embedded in the four instrumented elements. Automated measurements of strain and temperature are taken twice every hour. They are then analysed by CSIC researchers to derive the axial shortening of the instrumented elements along the whole length of the building, with an accuracy of about 0.1mm. This process is planned to continue throughout the construction.

The data clearly show the progressive shortening of the building (Figure 1). Since the concrete temperature is also being measured from the DFOS system, it is possible to estimate how much of the movement is due to thermal expansion and contraction. From this approach it becomes clear that thermal effects can be significant and at times account for up to 50 per cent of the total axial displacement of the columns. The measurements recorded to date have matched with the engineers' predictions, providing valuable reassurance to both the contractor and the designers.

This is a demonstrator project that is intended to (a) provide building performance data for calibrating design assumptions and calculations (b) help CSIC fine-tune the DFOS system design, installation and data processing techniques for monitoring tall buildings, and (c) give the construction industry confidence in using DFOS for similar applications. In addition, the embedded system will become a permanent installation within the building structure once the construction is completed, thus making it possible to assess the axial deformation of this tall building throughout its lifetime.

Operative installing fibre optic sensor cables

Figure 1. Axial displacement time history of one of the instrumented columns derived from the DFOS monitoring system (L0 = ground floor etc)



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Integrity testing

Project 2

of deep foundations using fibre optic methods

Benefit to
Designers, contractors

Impact and value
- improve integrity testing methodology
- provide more confidence in thermal methods for integrity testing

In the UK, the current industry standard to test the integrity of pile foundations is to use Crosshole Sonic Logging (CSL). However, thermal methods which use the temperature generated during cement hydration to assess the quality of cast in situ concrete foundations are being introduced. CSIC has been testing the use of distributed fibre optic sensing (DFOS) as a thermal method which provides a continuous temperature profile as an alternative to conventional point sensors. With DFOS, low-cost standard telecommunication fibre optic cables can be attached to several sides of the reinforcement cage of a foundation element in continuous loops. Several elements can be monitored at the same time on a single fibre optic circuit (single channel). Temperature measurements are obtained at close spatial intervals along the cage, and at short time intervals to record the evolution of the temperature profile of the element during concrete curing.

This approach was put into practice on a number of projects in collaboration with Cementation Skanska over the past 3 years who, with CSIC's support, reached commercial readiness with its own fibre optic technology system, CemOptics, in late 2015. Since then, the technique continues to be used by Cementation Skanska on an unprecedented scale for pile and wall integrity testing. Recently Cementation Skanska, Arup and CSIC have collaborated on writing industry specification guidelines[1] for integrity testing using fibre optic sensing.

However, there are still some very interesting questions about the use of thermal methods including understanding the influence of several factors related to soil and concrete properties on thermal data and the interpretation of quality or integrity. The EPSRC and Arup are funding two 4-year PhD CASE studentships at CSIC starting in the next academic year on developing a more systematic interpretation method to asses integrity through thermal data. This research will help improve industry confidence in the technology and have a positive impact on the field of integrity testing.

[1] ICE Specification for Piling and Embedded Retaining Walls, Third Edition, ICE Publishing, 2017.

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Optimising design costs

Project 3

of overhead line electrification foundations

Benefit to
Designers, contractors

Impact and value
- cost savings through more economical design
- design assurance

The electrification of extensive lengths of the UK's railway network over the next five years will require the construction of tens of thousands of posts and gantries to support power cables and associated overhead line equipment (OLE). These structures must support vertical loads and lateral moments associated with their own weight and that of the equipment as well as tensioning of the cables. They must also support lateral moments due to external factors such as wind.

Traditional design of OLE support structures is based on the empirical Office for Research and Experiments (ORE) method derived from full-scale field tests carried out in the 1950s. The application of analytical approaches adopted in modern design codes has led to more conservative and less economical designs of OLE support than the ORE method. The plans for electrification of the current network and that of HS2 offer an opportunity to revisit the economical and reliable ORE method and extend its design methodology to large 610mm diameter circular hollow section steel piles to asses higher in-service loading conditions.

This project, led by UKCRIC partner Southampton University and funded by Network Rail, aims to test full-scale OLE foundations and measure steel pile performance under large loads. CSIC, in collaboration with Southampton University, has installed fibre optic strain sensors on the heavily instrumented piles to directly measure the bending moments. In addition, wireless tilt sensors and accelerometers are employed to monitor the steep slope immedialely adjacent to the railway during loading.

This project could potentially result in significant cost savings if the results of field measurements can provide the necessary assurance to be applied to the design of future OLE foundations.

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Settlement monitoring of heritage structures

Project 4

Part of the Bank station capacity upgrade – St Mary Abchurch and Mansion House

Benefit to
Heritage property asset owners, tunnelling and monitoring industries

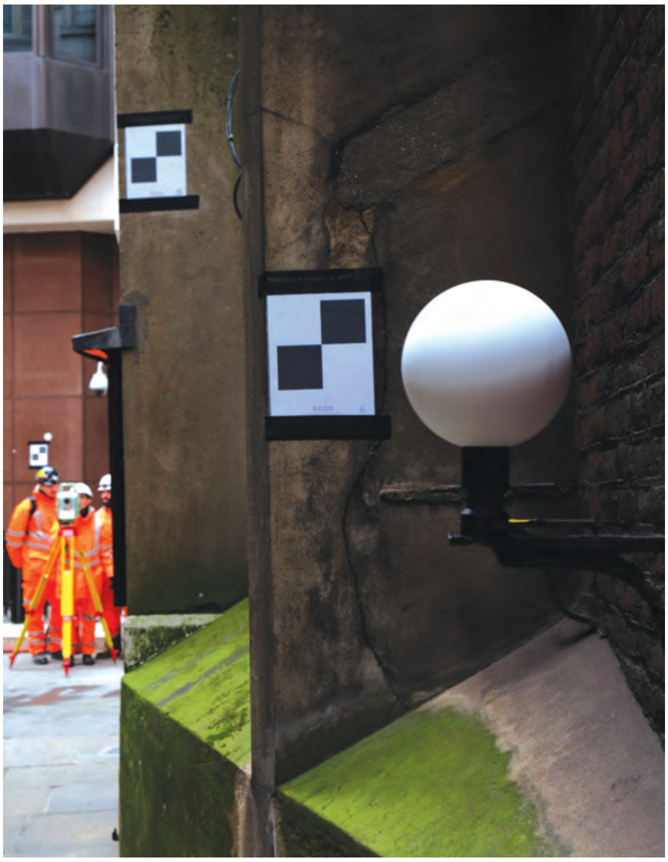
Impact and value
- assist in the protection of heritage structures
- provide important structural health monitoring data to guide decision making

The Bank station capacity upgrade involves the construction of new tunnels under several Grade 1 listed historic buildings. The proposed tunnels are in close proximity to Christopher Wren's St Mary Abchurch and George Dance's Mansion House.

While only negligible impact is expected in each building, there are significant uncertainties regarding the behaviour of the ground and the building during the scheduled tunnelling works taking place between 2017 and 2021, making monitoring a necessary mitigation measure. CSIC is collaborating with the contractor Dragados and its monitoring arm, Geocisa, under the guidance of London Underground, to monitor the structural response of these buildings with new generation sensing techniques, including fibre optic strain sensing, point cloud and satellite displacement monitoring.

The project will demonstrate the value of new sensing techniques in understanding the behaviour of historic structures affected by ground works. In particular, it will provide new insight into building deformation modes during settlements, which are poorly understood. Previously developed sensing methods applied to London Bridge and Leeds viaduct (page 14) monitoring projects have enabled this deployment including designs for fibre optic cables and fixings and point cloud comparison methods. The monitoring system will be managed with Geocisa, integrating the fibre optic data to their monitoring systems to support knowledge transfer. The project also involves training of Geocisa personnel for this purpose.

Laser scanning at Mansion House



Surveying at St Mary Abchurch

Sensing data will be used to provide a critical assessment of analysis methods for tunnelling-induced damage in historic buildings. Accurate modelling techniques and strategies will be identified and this information will be used to improve existing assessment techniques. New model calibration and updating frameworks will be developed to allow the quantification of uncertainty in engineering analyses and clarify how sensing information allows management of this uncertainty.

Employing new sensing techniques to monitor the behaviour of valuable and historically important buildings and structures offers reassurance to asset owners and managers. The detailed data will allow informed assessment and timely intervention, if necessary, to avoid potential costly remedial action.

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Translucent City
Project 5

Transforming the use of underground space

Benefit to

Smart cities stakeholders

Impact and value

- knowledge transfer
- efficiency and sustainability
- design optimisation

Underground spaces are an increasingly valuable commodity in land-constrained and highly populated cities. Currently, the use of these spaces has been expanding in a piecemeal manner. Constrained access and diverse economics of underground infrastructure for transport, energy, water and waste require an understanding of multiple, overlapping networked industries. It is only by carefully examining the system of systems that cross-sectoral optimisation can be considered.

Translucent City is a collaborative research project that brings focus to the adaptability of underground spaces within densely populated cities. The aim is to engineer a translucent city to radically transform the usage of the subterranean part of a city, with physical infrastructure woven together with virtual infrastructure, while considering the evolution of human behaviour when circumstances or infrastructure changes.

Led by CSIC as part of the Global Alliance (a collaboration between the University of Cambridge/CSIC, the University of California, Berkeley and the National University of Singapore), Translucent City will provide cross-disciplinary study that integrates the subterranean part of a city with the above ground 'visible' systems – an area of research that has, until now, been under examined.

The ultimate goal of this project is to develop new research to support novel, cross-sectoral design and urban standards that enable the seamless optimisation of physical and virtual infrastructure as a whole and the growth of innovation and new technologies in the three Global Alliance cities (London, Singapore and San Francisco) as a precursor to worldwide potential.

The translucent city is a frontier of knowledge that has potentially much wider benefits than improving the efficiency of engineering systems. It has the potential to transform the environmental, social and economic functioning of cities.

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Transitioning cities
Project 6

Enabling the evolution of smart cities

Benefit to

Professionals in cities and infrastructure management, city managers, engineers and urban designers

Impact and value

- foster understanding and collaboration between disciplines
- identify gaps and tools needed to deliver smart cities

The transition to 'smart' presents complex challenges. Many organisations working in Smart Infrastructure are ill equipped to develop and deliver solutions; professionals in cities and infrastructure management have not traditionally been trained in interdisciplinary collaboration. Without a culture of collaboration there can be no integrated solutions. There is a pressing need for built environment professionals who are trained in a broader range of disciplines and tools, bridging infrastructure and city management solutions and developing opportunities presented by the digital economy. CSIC is addressing this need through the Ove Arup Foundation Programme for Transitioning Cities.

Existing methods for assessing and analysing the operational needs of a city and the relationship with physical infrastructure are not 'joined up', and approaches to address them may be in tension. Additionally, industry and city governments lack the tools to understand and interpret the current abundance of data in order to support smart cities' decision-making processes and deliver best value from them.

This programme addresses the disciplinary gulf which currently exists between city managers, engineers and urban designers. It will catalyse and establish a significant ongoing research programme to address gaps and identify the digital tools required to deliver a smart city which benefits the citizens it serves. The four-year programme will result in a series of graduate-level and executive-level educational modules. It will deliver a series of academic and position papers and a research roadmap to bring focus to outstanding challenges. In addition, a competence framework for smart city professionals and an educational programme consisting of two strands – 'methods' and 'case studies' – will be developed.

The programme will be delivered by a team of experts from CSIC and will bring together academic colleagues from the disciplines of Civil Engineering, Land Economy, Architecture, Geography, Manufacturing Engineering and Computer Science to develop capacity and capability within UK industry to design, deliver and sustain smart cities and infrastructure solutions.

CSIC is grateful to the Ove Arup Foundation for providing funding to catalyse this project, enabling CSIC to develop the required research programme and educational outputs.

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WindAfrica

Project 7

Improving foundation design for wind turbines in developing countries

Benefit to
Designers

Impact and value
- design guidance for a better understanding of expansive soils
- cost saving
- sustainability

WindAfrica is a collaborative research project that aims to address challenges to the development of sustainable energy in Africa where more power generation is needed to meet existing and future demand. Despite a wealth of renewable energy resources, particularly wind, the growth of this type of power generation has been limited by the lack of design guidance for turbine foundations on unsaturated expansive soils found throughout much of Africa. Turbine foundations are subject to highly dynamic and concentrated loading. In areas of unsaturated expansive soil, the behaviour of which is complex and not well understood, foundations have to be designed on a project-by-project basis which can be cost prohibitive. Additionally, small movements in the foundations can trigger turbine performance problems leading to costly foundation replacement and decommissioning.

This EPSRC-funded three-year project aims to analyse data on the mechanics of partially saturated soil to provide guidelines for the construction of turbines. The project benefits from academic expertise from CSIC, Durham University and the University of Pretoria in South Africa and input from industry project partners including Parsons Brinkerhoff, Jones & Wagener and Gaia-Wind. It is the first of its kind to address geotechnical challenges on this scale.

Fieldwork, scheduled to begin this year, is located in Sudan where the soil is representative of a large part of East Africa. Extensive analysis will be completed on the collected field data, followed by physical modelling and numerical analysis. The combined data will inform a simplified semi-analytical model for foundation deformation and bearing capacity and provide foundation design guidelines for wind turbines in Africa.

Applying these guidelines will enable the growth of a sustainable energy market in Africa by reducing the current financial burden associated with constructing foundations for wind turbines. The knowledge transfer of this project means UK industry will gain a competitive advantage in a new area of construction.

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Mixed reality

Project 8

for automated solutions for construction progress monitoring

Benefit to
Asset owners, contractors, engineers, designers

Impact and value
- cost saving, time saving
- improved productivity and workflow
- increased accuracy for inspection – less error prone
- ability to work effectively remotely

Progress monitoring inspection is an essential part of any construction project and critical to maintaining workflow, productivity and performance targets. Overrunning on time and costs leads to unbudgeted expense and can jeopardise the financial model that secures profitability.

While inspection is crucial to the success of construction projects, current manual inspection methods are laborious, time consuming and error-prone, requiring subjective visual inspection, extracting information from detailed drawings and writing lengthy reports.

CSIC collaborators at the University of Cambridge Construction Information Technology (CIT) Laboratory are working with California-based company, Trimble, that provides technology for the construction, geospatial and transportation industries, and Microsoft, to develop an automated inspection process for construction progress monitoring. The Automated Progress Monitoring Inspection App uses Microsoft HoloLens (a computer headset that allows the wearer to view 3D digital models in the physical space) and multiplatform game engine Unity to create a semi-automatic inspection method that aligns the 3D as-planned model to the real world as-built environment. This app allows inspectors to bring the design model out of the office and on to the construction site and marks the first time a 3D model of buildings and bridges has been taken off the screen and put onto the real structure.

The HoloLens allows the wearer to walk through building construction sites and automatically visualise Building Information Models (BIMs) in full scale at their offices or superimposed on the real structure at construction sites. After automatically placing the 3D model to the correct height and orientation, the user manually aligns the model by moving it to fit the dimensions of the actual building. The new method compares the current as-built status (real world) with the as planned data (3D model) once the registration of the model to the real world is secured. A time attribute is added to every element and the comparison is done to enable accurate determination and recording of progress status. This information can be used to monitor actual progress and make time- and cost-saving interventions where required. In essence, this advance in automation allows engineers to see what is on or behind schedule.

The Automated Progress Monitoring Inspection App has been successfully used at CIT to inspect columns, walls, floors, panels and lights. The next step will be to deploy the App on a live construction site.

This project is funded by a European Commission Grant.

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Bridge inspector

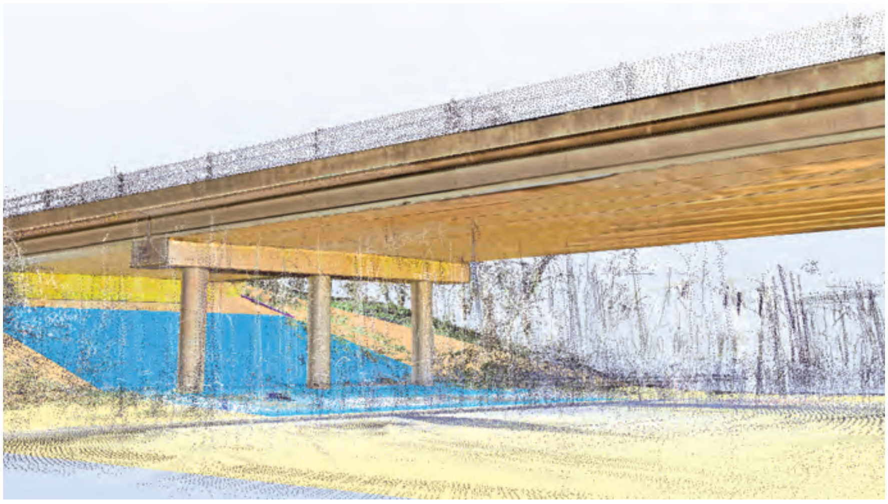
An automated approach to help prioritise bridge inspection programmes

Benefit to
Asset owners, asset managers, bridge inspectors

Impact and value
- improved safety
- cost saving, time saving
- increased accuracy for inspection – less error prone
- provides useful training tool for inspectors

Bridges are complex structures that are constantly exposed to changing temperatures, moisture and dynamic loading, making them difficult to inspect. Manual bridge inspection is a laborious, subjective, incomplete and costly procedure. Additionally, inspections that require protective equipment and mobile elevating work platforms bring associated risk.

This novel approach uses high-resolution images of the structure, which can be taken by local teams and sent to inspection engineers wherever they are based. These images are then automatically mapped onto 3D models of the respective bridge. The type of bridge defects a structure presents depends on its location and orientation which influence the conditions encountered. Experienced bridge inspectors focus their attention on these crucial locations. CSIC's Bridge Inspector method comprises a three-step process to mimic this approach. First, a machine learning classifier separates visually intact concrete from irregular patterns; the classifier has to learn to distinguish between expected deterioration and actual defects. The second step classifies the irregular findings into a defect category based on the individual appearance. Distinguishing defect categories is trained in a supervised manner using self-collected data and data repositories provided from the Department for Transport and local agencies. During the third step additional information, for example the orientation or location of a crack, is used to refine the defect types.



Fully-textured, real size as-is bridge model based on point cloud and high resolution imagery which allows for remote inspection using HoloLens

Viewing the bridge model in the office

Visual inspections to identify structural health issues, including spalls, scaling, efflorescence and freeze/thaw cycles, can be challenging as early signs of problems are difficult to see. Costs are high due to travel of inspectors to sites and, when required, closure of roads and traffic diversions to facilitate inspections. Ownership of bridges in the UK falls under the jurisdiction of various county councils and authorities which out-source inspection to a number of different companies. Bridge inspection data is not collected according to an industry standard or system and is often stored in a proprietary format.

Strategies have been developed to prioritise the various maintenance needs with the objective of maximising value for money (London Bridges Engineering Group, 2008[1]). Prioritisation processes generally include the importance of a structure for a road network, its condition for assessing safety risks for bridge users and impact on the lifecycle of a structure. Existing research methods for automated bridge inspection are able to detect one class of damage type based on images. A multiclass approach that also considers the 3D geometry, as inspectors do, is currently the focus of this research.

Finally engineers are able to inspect and assess the irregular areas of infrastructure from their office (remotely) as if they were standing on site in front of the real asset. Bridge defect data could potentially be collected during scheduled maintenance, making manual inspections less critical. Identifying defects early leads to savings in maintenance costs and could mean fewer large-scale repairs, keeping bridges open for longer and cutting traffic delays and congestion. Automating the inspection process reduces inspection costs and generates more accurate data to better inform more cost effective asset management.

This research project is supported by Trimble, the California-based company that provides technology for the construction, geospatial and transportation industries.

[1] London Bridges Engineering Group (2008). Phase 1 Maintenance Prioritisation for Highway Structures.

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Data-driven asset management

A framework for linking ISO and BIM standards for whole-life value

Benefit to
Asset Managers

Impact and value
- through-life management of assets
- better information for better decisions
- cost saving, time saving

The UK construction industry has been mandated to improve the design, delivery and maintenance of assets through the delivery of digital information. The focus of this research is how the advancement in technology within the construction industry, most notably Building Information Modelling (BIM) and Geographic Information Systems (GIS), can aid asset managers. The aim is to identify, for a given asset type, the information required for through-life management, and how to utilise such information within the BIM model.

BIM is the strategic approach to use information technology to create and manage information related to built assets during their entire life cycle. BIM is being implemented for design and construction, but its use for asset management and maintenance is only just beginning to be considered. Design data and asset information which would enable efficient management of built assets, although available, is not currently passed on to asset managers in a way that can be easily utilised.

This research, in partnership with Costain, will progress the use of BIM as the cornerstone of information management for asset maintenance and management (BIM levels 3 and 4). For a given asset type, the information required for through-life management and a method to link this to the BIM model to provide a fully integrated asset management platform will be identified.

The aim is to create a model-based framework approach to aid in the development of whole-life asset information requirements (AIR) linking the BIM 1192 standards with the ISO 55000 standards (Figure 1). A tool will be built that can automatically link AIR to Uniclass 2015 – a unified classification system for the construction industry. Uniclass 15 contains consistent tables classifying items of all scale from a facility such as a railway through to products such as a CCTV camera in a railway station. The asset information model will be validated for the organisation information requirements and objectives.

As the world of BIM L3 (Digital Built Britain) and UK Digital Economy beckons, there will be a strong focus of data-driven construction solutions. This research will set the foundations for the connected construction site and lead to future digital business models and developments around Internet of Things and the smart cities agenda.

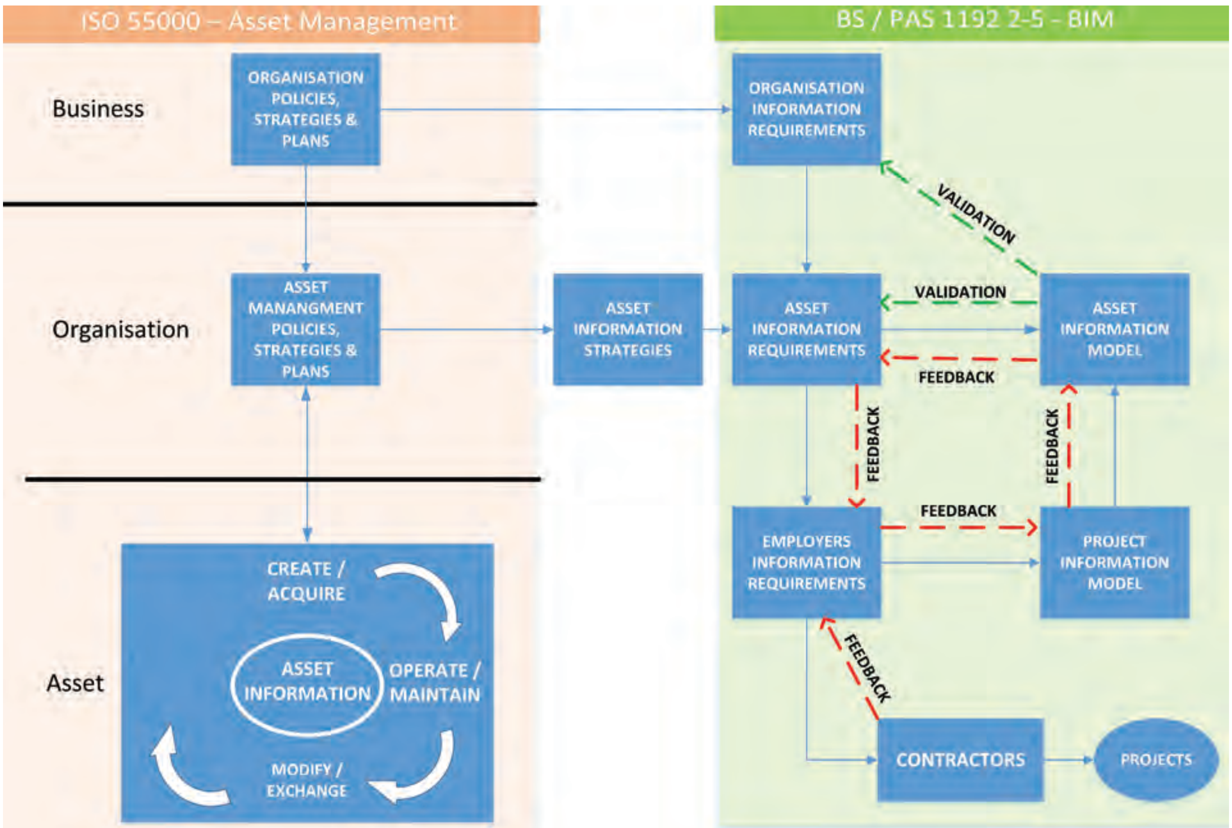

Figure 1. Asset Information Requirements – the alignment between the ISO 55000 standards and the BIM 1192 standards

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Tram vibration and impact monitoring

Project 11

Lowering maintenance costs and improving public acceptance

Benefit to
Rail owners and operators

Impact and value
- improved service through reduced vibration
- cost saving, time saving

The Vibration and Impact Monitoring of Tram Operations (VIMTO) research project aims to develop a vehicle-based automated system for track monitoring that may be permanently installed on service trams running on an operational network.

There are more than 290km of modern tramway in the UK alone, the majority of which runs through densely populated urban areas. The disturbance to building occupants caused by tram-generated ground-borne vibration presents a significant barrier to the expansion of tram networks in our cities. Tram operators must work continuously at track maintenance to keep noise and vibration within acceptable levels. Currently, this work relies on time-consuming and costly manual track inspections, typically undertaken fortnightly, to identify areas of deterioration before they become a significant source of vibration.

This EPSRC-funded collaborative project, working with industry partner Transport for West Midlands, the company responsible for the UK's Midland Metro tram network, has the potential to transform track maintenance operations and deliver two key benefits:

- reduced disturbance from tram operations, increasing the public acceptability of both the current network and Transport for West Midland's plans for future network expansion
- improved track monitoring efficiency, resulting in a more cost-effective maintenance programme

At present, the completed instrumentation has been installed on a service tram for a monitoring trial on the Midland Metro network. Data will be presented in the form of a vibration map of the Midland Metro network. This will highlight areas of the network which need maintenance to reduce noise and vibration levels.

Although the current focus of VIMTO is on tram operations, the proposed monitoring methodology is broadly applicable to other rail transport systems, including underground railways. Improved track monitoring leading to lower maintenance costs and increased public acceptability of trams directly supports the expansion of this more environmentally sustainable mode of transport in both domestic and international markets.

Tram in Birmingham city centre

The VIMTO project is developing a novel form of track vibration monitoring, whereby the trams themselves are used as the primary monitoring instrument. Low-cost instrumentation mounted on tram axle-boxes records vibration signatures simultaneously with positioning data to produce a map of the network in terms of its propensity to generate ground-borne vibration. The map offers real-time continuous monitoring of the network allowing asset managers to observe the rate of deterioration. This data is key to the formulation of an optimised maintenance strategy that eliminates costly track failures.

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Enabling implementation

CSIC works collaboratively and strategically with industry, government and academia to promote the adoption of Smart Infrastructure solutions and enable the marketplace. This shared expertise provides the guidance, standards, policies and knowledge to ensure that the UK remains the leader in innovative infrastructure and construction. Examples of the impact CSIC is delivering in shaping the strategic agenda for Smart Infrastructure and enabling its implementation in practice are outlined below.

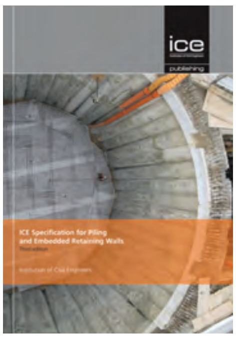
Smart Infrastructure and Construction journal

The first issue of Smart Infrastructure and Construction[1], ICE Publishing's new Proceedings journal, co-edited by CSIC Director Dr Jennifer Schooling and Professor Kenichi Soga, Department of Civil and Environmental Engineering, University of California, Berkeley, USA, was published in March 2017. This new ICE journal will provide a learned forum for documenting changes caused by the global adoption of emerging digital technology in the design, construction and management of infrastructure assets. These radical changes will lead to greater efficiency, economy, adaptability and sustainability in the way our infrastructure is delivered and operated.

ICE State of the Nation 2017: Digital Transformation

CSIC Director Dr Jennifer Schooling was a a member of the 2017 Steering Group for the report, State of the Nation 2017: Digital Transformation. The State of the Nation series of reports, published annually by the ICE, assesses the policy challenges for the UK's infrastructure networks and recommends actions needed to deliver improvements. The 2017 report calls on industry and government to use the modern Industrial Strategy to drive the uptake of digital technology and data in infrastructure design and delivery. By building upon pioneering work in digital engineering, government and industry could improve the performance of UK infrastructure and support economic growth. The full report is available on the ICE website[2].

ICE piling standard



Arup, CSIC and Cementation Skanska have collaborated on contributions to the ICE Specification for Piling and Embedded Retaining Walls[3] (SPERWall) published in 2016. This reference document, which is revised every 10 years, is used by the industry for specifying the testing and instrumenting of foundations.

Report: Promoting adoption of Smart Infrastructure solutions in the transport sector

CSIC was commissioned to prepare a report outlining a series of policy recommendations for the government's Department for Transport (DfT) Chief Scientific Advisor. The report, titled Promoting Adoption of Smart Infrastructure Solutions in the Transport Sector[4] and published in October 2016, outlines the key points arising from a workshop organised by CSIC on behalf of DfT's Scientific Advisory Committee. The workshop convened an invited group of business leaders, infrastructure managers, strategists and academics to discuss the importance of the continued development and deployment of smart technologies in the areas of transport infrastructure and related construction. Listing a series of recommendations for future planning, the report responds to government policy in recent years and seeks to explore the role of new technologies in the planning, construction and maintenance of the UK's transport infrastructure. Its aim is to provide a framework for future development that makes for a 'smarter', leaner, greener and more cohesive approach to transport infrastructure. Further to this, CSIC was approached by the Centre for Science and Policy at the University of Cambridge to develop and deliver a series of professional development workshop for a cohort of 20 DfT policy professionals. These workshops ran between March and May 2017, and focussed on identifying policy actions which could help to move smart infrastructure condition monitoring approaches from the realms of repeated demonstration projects to becoming standard practice. This has brought Smart Infrastructure into the mainstream of discussion, and it is hoped that the policy projects identified will make a real difference to generating uptake of Smart Infrastructure solutions in the DfT's portfolio of transport assets.

Responding to the National Infrastructure Commission

Professor Lord Robert Mair was a member of the Executive Group of the National Needs Assessment for the National Infrastructure Commission (NIC) providing input to and blueprint for NIC's national infrastructure assessment. Further to this, in response to a request from the Chancellor of the Exchequer, the NIC launched a four-week call for evidence on 15 February this year to identify which emerging technologies have the most potential for improving infrastructure productivity. CSIC's report for the DfT was specifically mentioned in the Chancellor's request to the NIC as relevant work to be built upon. In a joint response to the call with the Civil Engineering Division, at the Department of Engineering, University of Cambridge, CSIC proposed three areas of 'smart' innovation key to the future success of ensuring the capacity, efficiency, reliability and resilience of UK infrastructure that have the potential to create systemic change over the next 10 - 30 years: Digital Built Britain, sensor technology and data analysis and interpretation. The NIC will make recommendations to government on what actions it should consider to support deployment. The Commission's assessment and recommendations will be reported by the end of 2017.

Best practice and technology guides

CSIC's leading experts across the fields of asset management, wireless sensors, distributed fibre optic strain sensing and bridge monitoring have written four best practice and technology guides published by the ICE. The guides are intended to be far-reaching, informing and supporting the construction industry, infrastructure owners and operators and the manufacturing, electrical and information sectors on the installation and operation of novel sensing technologies for asset monitoring and management. The titles comprise:

- Whole-Life Value-Based Decision Making in Asset Management by Rengarajan Srinivasan and Ajith Parlikad
- Wireless Sensor Networks for Civil Infrastructure Monitoring: A Best Practice Guide by David Rodenas-Herráiz, Kenichi Soga, Paul Fidler and Nicholas de Battista
- Distributed Fibre Optic Strain Sensing for Monitoring Civil Infrastructure: A Practical Guide by Cedric Kechavarzi, Kenichi Soga, Nicholas de Battista, Loizos Pelecanos, Mohammed Elshafie and Robert J Mair
- Bridge Monitoring: A Practical Guide by Campbell R Middleton, Paul Fidler and Paul J Vardanega.

The guides are available from the ICE Bookshop[5].

Independent design panel for High Speed Two

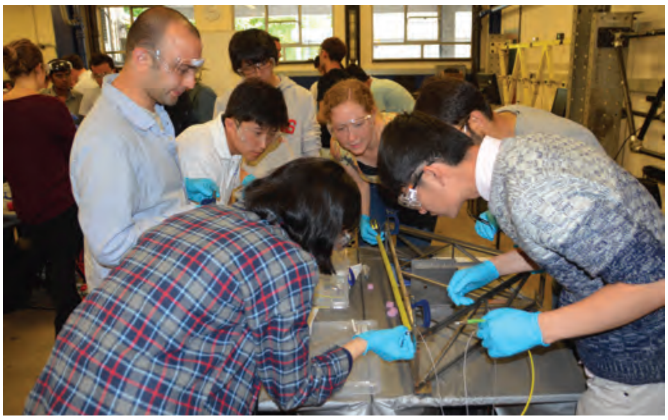
Campbell Middleton, Professor of Construction Engineering at the University of Cambridge and CSIC Co-Investigator, has been appointed to the independent design panel for High Speed Two. The panel is the project's independent advisor on design and includes specialists in procurement, engineering, architecture, town planning, rail, branding and community engagement. Professor Middleton joins as an expert on bridge design. Before beginning his academic career with the University of Cambridge, Professor Middleton spent almost a decade in professional engineering practice in the United Kingdom and Australia. He is Chairman of the UK Bridge Owners Forum and also acts as a consultant specialising in bridge engineering and smart technologies for construction.

International Conference on Smart Infrastructure and Construction (ICSIC) 2016

The International Conference on Smart Infrastructure and Construction (ICSIC) 2016, organised and hosted by CSIC, attracted world-leading academics and practitioners from 23 countries from the fields of infrastructure planning, asset management and sensing. The unique combination of specialist fields and disciplines at ICSIC 2016 brought focus to the power of smarter information with the aim of confronting persistent barriers and identifying and developing novel and proactive solutions. Key issues identified during discussions included: the need for a broad, multi-disciplinary research community to collaborate to improve results and provide a sound evidence base; the urgency for industry to step up and implement models, tools and techniques in an efficient manner to avoid an innovation lag; the need for more initiatives like Crossrail's Innovate18 programme that provides an exemplary template for industry; and a new breed of 'digital native' engineers to ensure 'smart' techniques and technologies are effectively adopted at every level. The conference proceedings are available from the ICE Bookshop[5].

Asia-Pacific-Euro Summer School on Smart Structures Technology (APESS) 2016

Civil engineering students from around the world travelled to Cambridge to learn from international experts in the field of smart structures for a three-week summer school sponsored by CSIC. Students attended lectures from an international panel of academics and participated in a group challenge, instrumenting a structure in a lab environment in order to gain hands-on experience with fibre optic and wireless sensing systems. The APESS programme included the International Conference on Smart Infrastructure and Construction (ICSIC) and the International Workshop on Advanced Smart Materials and Smart Structures Technology (ANCRiSST2016), allowing students to learn about the latest technology and techniques in Smart Infrastructure and construction from the pioneers in the field. This event marked the first time the summer school has taken place in Europe, with previous programmes taking place in the United States and Asia.



APESS 2016 students learning about instrumentation as part of a team challenge

1 www-smartinfrastructure.eng.cam.ac.uk/news/ice-smart-infrastructure-and-construction-journal
2 www.ice.org.uk/media-and-policy/policy/state-of-the-nation-2017-digital-transformation
3 ICE Specification for Piling and Embedded Retaining Walls, Third Edition, ICE Publishing, 2017.
4 www.gov.uk/government/uploads/system/uploads/attachment_data/file/559770/dft-science-advisory-council-condition-monitoring-and-intelligent-infrastructure-report.pdf
5 www.icebookshop.com

> “ CSIC provides strategic leadership to the infrastructure industry. Smart infrastructure is transforming how our infrastructure is designed, delivered and used. Working in collaboration with the Centre has enabled Costain to provide a greater range of technology solutions that continues to improve the performance of our customers’ business.

Tim Embley
Group Innovation and Knowledge Manager, Costain
CSIC Steering Group Member

Leadership

Professor Lord Robert Mair CBE
Sir Kirby Laing Professor of Civil Engineering
Head of CSIC

Lord Robert Mair is the Senior Vice-President of the Institution of Civil Engineers (ICE) and has been elected President for ICE's bi-centenary year 2017 - 2018. He is a Fellow of the Royal Academy of Engineering and a Fellow of the Royal Society. He was formerly Master of Jesus College, Head of Civil Engineering at the University of Cambridge and Senior Vice-President of the Royal Academy of Engineering. His research group at Cambridge specialises in the geotechnics of tunnelling and underground construction. Prior to his appointment to a Professorship at Cambridge he worked in industry for 27 years, and was a founding partner of the Geotechnical Consulting Group. He has advised on numerous tunnelling and major civil engineering projects in the UK and worldwide, including the Jubilee Line Extension, Crossrail and HS1. He is Chairman of the Science Advisory Council of the Department for Transport. He was appointed an independent crossbencher in the House of Lords in 2015 and is a member of its Select Committee on Science and Technology.

Dr Jennifer Schooling
Director of CSIC

Dr Jennifer Schooling was appointed Director of CSIC in 2013. Dr Schooling has secured £7.6M in grant funding from EPSRC and Innovate UK for the Centre, including an additional five years' core funding awarded to enable the Centre to expand its valuable work. She is founding Co-Editor-in-Chief of the Smart Infrastructure and Construction Proceedings journal (ICE) and a member of PAS185 smart cities security standard steering group and the UKCRIC standing committee. She has also recently served as a member of ICE's State of the Nation 2017 'Digital Transformation' Steering Group, the Tideway Innovation Forum and Tideway Academic Advisory Group. Prior to joining the Centre, Dr Schooling worked for Arup, leading the firm's Research Business. She also worked with the Modern Built Environment Knowledge Transfer Network leading on the development of the agenda for the emerging Future Cities Catapult. Before joining Arup, Dr Schooling worked for Edwards Vacuum (then BOC Edwards) as a manager for New Product Introductions.

Executive Committee

Dr Ruchi Choudhary
Reader in Architectural Engineering
Prof Daping Chu
Head of the Photonics and Sensors Group
Dr Matthew DeJong
Senior Lecturer in Structural Engineering
Dr Cedric Kechavarzi
Senior Research Associate
Prof Lord Robert Mair CBE
Sir Kirby Laing Professor of Civil Engineering
Prof Campbell Middleton
Laing O'Rourke Professor of Construction Engineering
Dr Ajith Parlikad
Senior Lecturer in Industrial Systems
Dr Jennifer Schooling
Director of CSIC

International Advisory Group

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University College London
Prof Yozo Fujino
Yokohama National University, Japan
W. Allen Marr
Founder and CEO of Geocomp
Prof Thomas O'Rourke (Chair)
Cornell University, USA
Prof Bill Spencer
University of Illinois, USA
Prof Paul Wright
University of California, Berkeley, USA
Prof Hehua Zhu
Tongji University, China

Steering Group

Simon Abbot
Network Rail
Karen Alford
Environment Agency
Francine Bennett
Mastodon C
Dr Keith Bowers
London Underground
Prof John Burland CBE (Chair)
Imperial College, London
Volker Buscher
Arup
Robert Dean
Network Rail
Tim Embley
Costain
Tom Foulkes
Independent Consultant
Steve Hornsby
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HS2
Vlad Palan
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Richard Ploszek
Infrastructure and Projects Authority
David Pocock
CH2M
Stephen Pottle
Transport for London
Dr Scott Steedman CBE
British Standards Institution (BSI)
John St Leger
HS2

Our people

Investigators

CSIC benefits from contributions made by a number of Investigators who are all experts in their specialist fields. Our Investigators work across a range of academic disciplines enabling a productive and effective synergy.

Dr Giovanna Biscontin
Lecturer in Geotechnical Engineering

Dr Ioannis Brilakis
Laing O'Rourke Lecturer in Construction Engineering

Dr Ruchi Choudhary
Reader in Architectural Engineering

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Prof Duncan McFarlane
Professor of Industrial Information Engineering

Prof Cam Middleton
Laing O'Rourke Professor of Construction Engineering

Dr Ajith Parlikad
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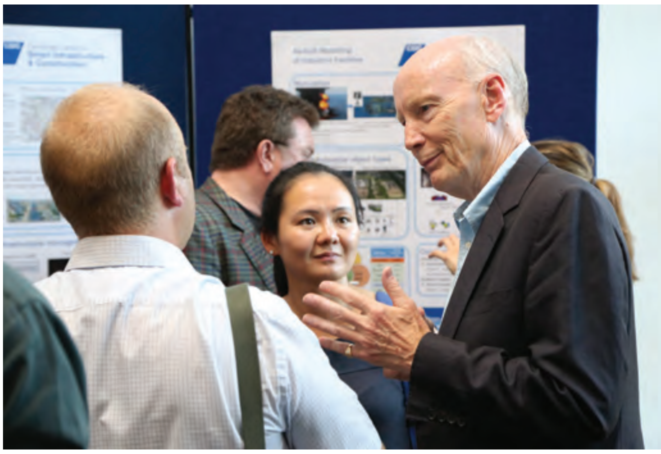
Prof Ashwin Seshia
Professor of Microsystems Technology

Dr Elisabete Silva
Senior Lecturer in Spatial Planning

Prof Kenichi Soga
Chancellor's Professor, University of California, Berkeley

Dr James Talbot
Lecturer in the Performance-based Design of Structures



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Samantha Archetti
Programme Administrator
Amelia Burnett
NRFIS Project Manager
Paul Fidler
Computer Associate
Dee Dee Frawley
Communications Manager
Peter Knott
Senior Technician
Phil Keenan
Business Development Manager
Lisa Millard
Communications Associate
Jason Shardelow
Technician
Tianlei Wu
Finance Manager

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Dr Sinan Açıkgöz
Dr Liam Butler
Dr Nicky de Battista
Dr Andrea Franza
Dr Cedric Kechavarzi
Dr Zhenglin Liang
Dr David Rodenas Herráiz
Dr Yi Rui
Dr Xiaomin Xu

Research Associates who have moved on during the year

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