UNIVERSITY OF CAMBRIDGE

Transforming infrastructure through smarter information

Annual Review 2020

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

CSIC Partners

Infrastructure clients (owners and operators)

- CERN
- HS2
- highways england
- Crossrail
- bp
- Transport for London
- Environment Agency
- EDF Energy

Consultants, contractors and asset managers

- Costain
- Jacobs
- Mott MacDonald
- Laing O'Rourke
- Cementation Skanska
- Arup
- Plowman Craven
- FDH Infrastructure Services
- geobear
- Royal HaskoningDHV
- hyperion infrastructure consultancy

Technology and information supply chain

- AssetScape
- Senceive
- ciria
- chartered ices
- 8power
- Topcon
- Sintela
- Geotechnical Observations
- Bentley
- Epsimon
- OptaSense
- Purrmetrix

Contents

CSIC

Foreword

Andy Mitchell CBE
CEO Tideway
Co-Chair Construction Leadership Council

> Even incremental change is not good enough – we have to do much more for much less, and quickly. Our economy needs this, and our impact on the environment demands this.

I am really pleased and encouraged to see this year's Annual Review from CSIC. I am writing this as most of the world is in some form of lockdown from the global Covid-19 pandemic, with huge restrictions on our activities, and with the construction industry worldwide heavily impacted by what we can and cannot do. We only have to look at the role that available technology is having in how we are dealing with this situation, with the ability of so many people to work remotely and stay in contact with colleagues, family and friends in a way that simply would not have been possible even five years ago. Change can happen, and it can happen very quickly. For all the wrong reasons we are also seeing just how much difference we can make to our environmental impact on the planet by changing what we do and how we do it.

As we look to the future of construction amongst so much uncertainty, one thing is clear for the Construction Leadership Council – as we all work to get the industry back up and running again, we cannot and must not simply go back to doing what we were doing before, designing, building and managing infrastructure in the same way. Even incremental change is not good enough – we have to do much more for much less, and quickly. Our economy needs this, and our impact on the environment demands this. I would urge everyone who reads this to embrace the thinking behind CSIC's 2020 Annual Review, and to work with others to accelerate the better decision-making that this Review showcases so well.


THE CROWN
WELCOME TO SOUTHSIDE
OFFICES TO LET
NCP

Introduction

Professor Lord Robert Mair CBE
Head of CSIC
University of Cambridge

The underpinning theme of this Annual Review is the use of data from real performance to enable better decision-making for reducing carbon, increasing resilience and preserving resources. There is increasing importance being placed on our national infrastructure and its considerable value to society and to our economy. Its engineering, management, maintenance and upgrading all require innovative thinking to minimise the use of materials, energy and labour while still ensuring resilience. National and local infrastructure in the UK need to be fit for purpose for supporting societal development in a changing world, especially in the light of both the Covid-19 crisis and the net zero carbon agenda. There is considerable potential for innovations and new technologies to improve performance and value through reducing construction costs and updating design methodologies. Such developments are best achieved by close collaboration between academia and industry – the keystone of CSIC's philosophy.

In his Foreword, Andy Mitchell highlights the importance of recognising the rapid changes to practice that have arisen from the Covid-19 pandemic and how these can make a substantial difference to our environmental impact on the planet. He rightly says that post Covid-19 we must not revert to designing, constructing and managing infrastructure in the same way as before; we have to find ways of doing much more for much less – both for the economy and for the environment. Our Director of CSIC, Jennifer Schooling, builds on this, emphasising the principal focus of CSIC as learning from the real performance of our infrastructure – only with measurement and data can decision-makers make step changes in how we design, construct, operate and maintain our built environment. She draws attention to the urgent need for collaborative action to achieving such step changes in order to reach net zero carbon by 2050 – the Covid-19 crisis demonstrating how it is possible to act very quickly and effectively. Tim Embley enlarges on this theme, with a call-to-arms for industry and academia to work together to accelerate rapid change, exploiting digital technologies, and establish a smart and sustainable infrastructure industry.

This Review includes details of our industry secondments which are a highly successful way of integrating CSIC's new technologies with industry practice. It also presents a number of case studies focusing on the use of data and smart infrastructure solutions. One of these case studies describes a data-driven framework to better target domestic energy policies, decarbonising domestic heating being a high priority for the route to net zero carbon; CSIC researchers have been working in close collaboration with The Alan Turing Institute to optimise the use of data to support more effective urban energy policies. Three case studies cover applications of innovative fibre optic strain technology: one applied to a possible early warning system for identifying potential sinkholes; another to a unique example of monitoring performance of large under-reamed piles intercepted by tunnelling; a third to the structural monitoring of various elements of our newly completed Civil Engineering Building. A further case study describes a new asset management methodology in which a line of sight from asset information to organisational objectives enables organisations to be agile in their response to extreme weather events and climate change. The final case study covers the development of a new digital strategy to support transport infrastructure investment and council policy goals in Cambridge to improve air quality and congestion.

Research projects are the backbone and engine house of CSIC's developments of innovative solutions for transforming infrastructure; some of the latest ones are described in this review. One concerns affordable robotics to support material efficiency, productivity and sustainability in construction of concrete buildings. Another covers the development of new instrumentation and analyses to estimate seabed cable fatigue, a topic of increasing concern for the resilience of offshore wind farms. A third project addresses emerging sensor technologies for the structural assessment and deterioration detection of highway assets, involving a systems integration approach bringing together a range of sensing technologies, computer vision and data analytics. Another project describes a proposed inspection system based on building digital twins for monitoring building environmental conditions; this has the potential for implementing smarter techniques for facilities management. A thought-piece highlights the importance of curation, analysis and management of high-quality data for optimising the performance and maintenance of our infrastructure.

These articles, case studies and research projects illustrate CSIC's strong commitment to providing leadership in exploiting data from sensing real infrastructure performance to reduce carbon, increase resilience and preserve resources.

Data-driven decision-making for smart sustainability

Dr Jennifer Schooling OBE
Director of CSIC
University of Cambridge

> Collaborative action will be crucial to securing the changes required to reach net zero by 2050; the consequences for not acting now will be devastating for many. There is much to do in a short time, but the Covid-19 crisis has demonstrated that when we need to, we can overcome challenges and act quickly.

To measure is to know. If you don't measure it, you cannot improve it.

Lord Kelvin, 1883

Before the current Covid-19 pandemic outbreak, my strategic thinking was very much focused on the global grand challenges of zero carbon, resource constraint and resilience. It still is. The crisis, rather than being a distraction from these issues, throws them into sharper relief. It represents both a major hazard and a great opportunity for achieving real progress against these challenges.

Despite the Covid-19 pandemic having a dramatic impact on all our lives, its impact on global CO_2 emissions has been relatively small, as shown by the graph on the next page. Our trajectory for recovery must not return to pre-pandemic levels – we must do more.

Collaboration is critical. If industry, government and academia work together, we can create a framework for recovery to embed low-carbon, low-waste outcomes into projects, with the potential for real transformation in industry practice. The stakes are high; if we fail, we risk creating an even greater burden for future generations to deal with.

In order to improve performance, we need to measure it – and this has long been the focus of CSIC's work. Learning from the real performance of our buildings and infrastructure assets to inform how we design, construct, operate and maintain our built environment is the cornerstone upon which CSIC's philosophy rests.

Over the last year, we have been working with partners to explore how we can help industry implement this approach to deliver on the zero carbon agenda. Our 'Smart Sustainability'[1] paper has gained real traction, and resulted in us engaging widely. Our most recent round table event, held in March 2020, brought together policy makers, clients and the supply chain to address short and longer-term actions we can take towards 'Achieving Zero Carbon', with a focus on pragmatic solutions that can save carbon now.

We are not alone – the Institution of Civil Engineers (ICE) State of the Nation report for 2020 is focused on net zero carbon, and i3P (Infrastructure Industry Innovation Partnership) identifies 'preparing construction for a zero carbon world' as one of four strategic innovation investment priorities, working to shape an industry carbon reduction programme through innovation and collaboration. CSIC is supporting both initiatives.

Our sector needs to innovate rapidly to change the way we deliver, manage and operate infrastructure, bringing the outcomes of the best research into practice much more quickly, and at scale. Our infrastructure and construction organisations must recognise the true value of data, adopt smart infrastructure solutions and apply data-centric engineering to operate more efficiently and productively – and embed whole-life value into everyday business. Such innovations offer a competitive edge to UK organisations competing in international markets in an increasingly resource-constrained future[2].

The value of infrastructure in use is substantially greater than infrastructure in development;[3] smart infrastructure enables us to secure more from existing assets, supporting asset owners to increase capacity and resilience and improve services. Optimising the performance and resilience of our infrastructure estate also allows us to consider no-build solutions. Considering our infrastructure as a system of systems which enables human flourishing enables us to plan and manage infrastructure differently, setting objectives in terms of outcomes for people, society and the environment[4].

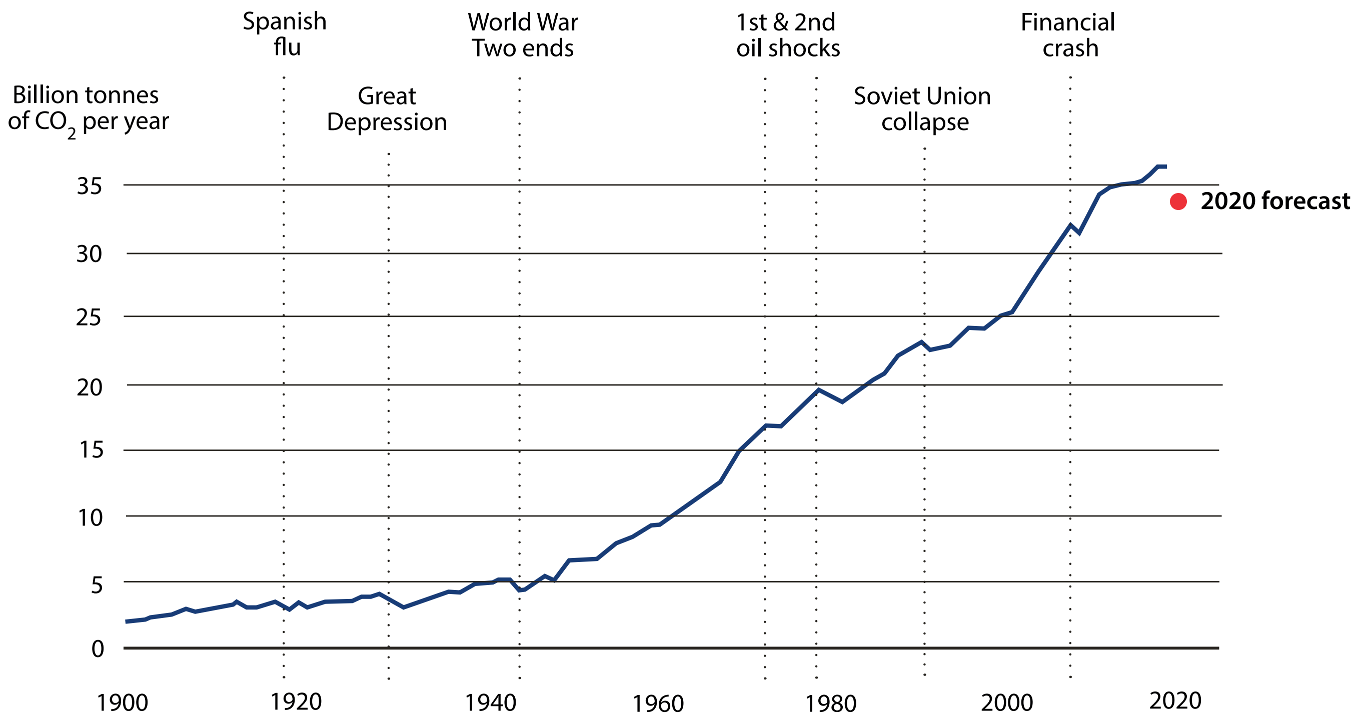
CSIC is now planning its research focus for the next five to 10 years. Our future strategy will build on the momentum CSIC has created, bringing together clients, industry, policymakers and academics to develop the emerging market for smart infrastructure solutions to address the grand global challenges of resource constraint, resilience and zero-carbon. We have assembled a cohort of committed industry partners, academics and aligned organisations, including The Alan Turing Institute, to collaborate in delivering transformative research and innovation to address key industry challenges.

We will work with our industry partners and associated organisations to identify barriers to implementing change, interrogate data and share risks, building upon our convening power to catalyse the transformation of infrastructure and construction at scale.

Collaborative action will be crucial to securing the changes required to reach net zero by 2050; the consequences for not acting now will be devastating for many. There is much to do in a short time, but the Covid-19 crisis has demonstrated that when we need to, we can overcome challenges and act quickly.

There has been a swift and effective response from almost every organisation, changing the structure of daily operation to work productively and remotely, and demonstrating the use of technologies in ways that we would all have thought impossible just a matter of weeks ago. Achieving zero carbon requires this level of response too – we've seen the possible and now we have to keep working together to make the seemingly impossible, possible.

Global CO_2 emissions, 1900 – present



Graph courtesy of BBC. Source: Pep Canadell (2012): Global Carbon Project – 2016 Global Carbon Budget. CDIAC. doi:10.3334/CDIAC/GCP_2016

Despite the Covid-19 pandemic having a dramatic impact on all our lives, its impact on global CO_2 emissions has been relatively small, as shown by this graph.

[1] Smart Sustainability: Exploiting data in engineering to mitigate climate change 2019
www-smartinfrastructure.eng.cam.ac.uk/system/files/documents/smartsustainability.pdf
[2] Infrastructure Carbon Review 2013
www.gov.uk/government/publications/infrastructure-carbon-review
[3] Smart Infrastructure: Getting more from strategic assets 2017
www-smartinfrastructure.eng.cam.ac.uk/system/files/documents/the-smart-infrastructure-paper.pdf
[4] Flourishing Systems: Re-envisioning infrastructure as a platform for human flourishing 2020
www-smartinfrastructure.eng.cam.ac.uk/news/flourishing-systems-re-envisioning-infrastructure-platform-human-flourishing

Infrastructure data insights for a sustainable and resilient future

Tim Embley
Group Research & Innovation Director
Costain

> If our industry is going to build a sustainable future, we must continue to bring leading-edge solutions into practice, with technology at the front and centre in everything we do. Data is the new currency for making the right decisions and smart infrastructure is the new practice in our engineering provisions.

Our global society faces unprecedented times. There have never been so many pressures on our industry and the infrastructure systems we deliver. External threats from climate change, weather extremes, terrorist violations, cyber penetration and recently Covid-19 are just some of the frontline challenges. Technological advancement, innovation and human ingenuity are combining to confront these challenges and drive the changes required to create a sustainable future for generations to come.

No one person or organisation can resolve these issues – we must all contribute to deliver a better outcome through the decisions we make both in the short and in the long term. Technology is an integral part of our tool kit but not a solution in itself; we must make decisions to ensure our industry creates a resilient built environment while respecting resource constraint within the natural environment which must be sustained.

Leaders across the infrastructure and construction industry have researched, innovated and developed new services in collaboration with our clients, bringing smart digital solutions to market and challenging existing business models to focus on better outcomes. Our industry is short of resources, both material and human, and there has never been a better time to work collaboratively to adapt, embrace and scale-up new solutions to make yesterday's innovation today's norm. The Covid-19 pandemic demonstrated how quickly and effectively we can act when circumstances demand urgent response; our infrastructure systems were critical in moving key workers and mobilising society and our communication systems essential to support remote working.

If our industry is going to build a sustainable future, we must continue to bring leading-edge solutions into practice, with technology at the front and centre in everything we do. Data is the new currency for making the right decisions and smart infrastructure is the new practice in our engineering provisions.

Collaboration to secure best outcomes for our industry and the people it serves is already happening and brings opportunity for positive change at scale. CSIC collaborates widely to accelerate implementation of smart infrastructure solutions, working with a range of organisations including i3P, fostering collaboration and innovation across infrastructure clients and their supply chains. Industry alignment with the Construction Leadership Council demonstrates how our sector is uniting important agendas to become a unified force for change. We are now a mature industry that must be agile and adapt quickly. We are embracing innovation as part of the trusted engineering solutions we support to enable society to function and flourish and the global ecosystem to prosper. A 'digital mind set' has to be front and centre of business, engineering and professional decisions as we champion smart infrastructure in everything we do. Digital will help predict the future, benchmark with the past, make real-time decisions today and enable better outcomes for society.

As industry leaders and influencers we are all responsible for the choices we make; we can refer to the Sustainable Development Goals to provide us with a framework for common good and to influence others that shape our industry. Financial decision-making dictates business models and commercial decisions. We welcome UK Government's review of the HMRC Treasury Green Book and the Five Case Model for business to consider a sixth case of sustainability when forming the business case for investment decisions. We welcome projects that receive investment from Green Bonds and the private sector who put emphasis on social value through their investment.

As you read this Review, please think of one action that you or your organisation can take – and do it well so it becomes your new norm and part of your business success. Let's work together to accelerate change and establish an industry of smart and sustainable infrastructure that is resilient and adaptable.

The year in numbers

£2.8m Funding won

178 Academic publications

29 Proofs of concept and demonstrators

10 Secondees

64 Knowledge exchange events

31 CSIC partners

56 Industry collaborators

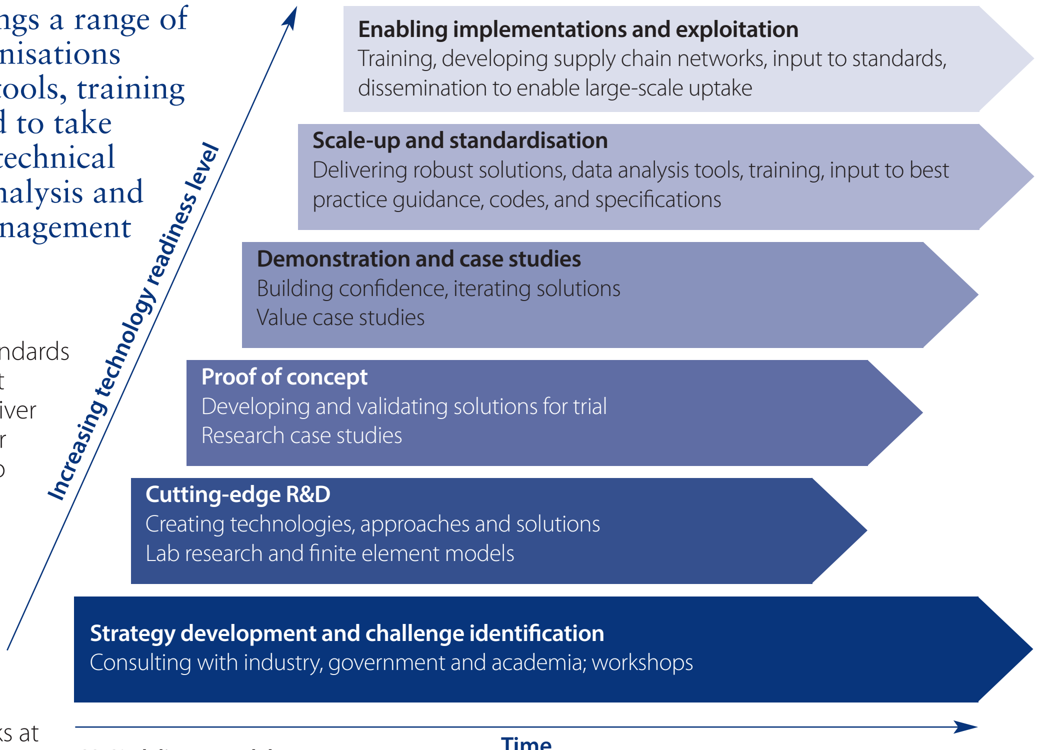
2838 Citations

17 Trade articles

Work with us

Working with CSIC brings a range of benefits to partner organisations including access to the tools, training and knowledge required to take advantage of the latest technical developments in data analysis and interpretation, asset management and sensor technology.

CSIC collaborates with partner organisations across policy, standards and industry adoption to effect transformative change and deliver benefits to all stakeholders. Our collaborative work is helping to establish the UK as a global leader in sustainable smart infrastructure solutions.



CSIC's delivery model

Sharing our knowledge, skills and information is key to advancing industry adoption of innovative solutions. CSIC works at a number of strategic levels to influence and inform the changes required to secure greater efficiency in design and performance, a low-carbon society, sustainable urban planning and management and improved health and productivity.

Deployment and business development

Testing new technologies and tools at live projects is central to CSIC's mission to accelerate the timeframe for innovations to become part of the industry mainstream. Our business development and knowledge transfer team works with industry to identify and understand real challenges to design, develop and deliver effective and repeatable solutions. CSIC collaborates closely with partner organisations to bring benefit and value to both parties and the wider infrastructure community.

Innovating the value chain

CSIC works with partners to support development of new sensors, monitoring systems and data analytics to provide information to better understand the whole-life performance of our infrastructure and enable better asset management and operational decision-making.

Training and dissemination

CSIC drives the information and knowledge sharing key to advancing industry adoption of innovative solutions through a range of routes including: specialist training courses held in the purpose-built CSIC Smart Infrastructure and Construction lab situated at the National Research Facility for Infrastructure Sensing (NRFIS); on site at a live project or at a partner's facility; workshops; roundtables; annual Partner Strategy Day; best practice guides; and case studies, all of which you will read about in this Review.

Partnerships

Partnerships designed to suit a range of organisations include: Full Partners; SME Partners; Micro Partners (fewer than 10 employees); and Associate Partners, which are typically non-commercial, non-profit making organisations. Partner benefits include engagement in CSIC's strategic research, opportunities to second staff to CSIC (see pages 10 and 11) and access to bespoke training, partner events and specialist workshops.

Get in touch

Working with CSIC creates a range of benefits derived from a strategic collaboration between academia, industry and policy. If you would like to find out more about how we work or collaborate with us please contact:

Partnership
Dee Dee Frawley
ddf21@cam.ac.uk

Knowledge transfer and training
Dr Cedric Kechavarzi
ck209@cam.ac.uk

Business development
Phil Keenan
ptk23@cam.ac.uk

Work with us

Working with industry – CSIC secondments

CSIC's secondment programme is integral to knowledge sharing with our partners and advancing industry adoption of innovative solutions to engineering challenges. We have welcomed 23 secondees over the years, and this year CSIC has worked with 10 secondees – you can read more about two of the projects in the Case Study section of this Review. The 2020 secondment cohort has engaged with a range of CSIC's technical developments in data analysis and interpretation, asset management and sensor technology, for which the secondees apply for the benefit of their own organisations.

Portcullis House, part of the Parliamentary Estate, London

High-growth environments and their potential to become Zero Carbon Business Communities

Andrea Imaz, Perkins+Will and Mingda Yuan, CSIC Researcher

This project explores high-growth business environments in South East England with a twofold aim: understanding the evolving patterns of these successful communities and identifying feasible pathways to achieve energy improvements through community-level collaborations based on the characteristics of their built environment. This research-focused statistical analysis was designed to support urban design and planning processes at Perkins+Will with a special focus on employment locations and their energy performance, providing better insight into the description of urban ecosystems informing both academia and the design professions.

"We approach this secondment as an opportunity to improve our data analysis knowledge and provide better informed-design processes to the communities and employment locations we work with. During the process we have been able to assess our analytical methodologies and identify valuable metrics to be implemented as performance indicators for sustainable and resilient urban design projects or planning policies. Different advanced statistical techniques and recent machine learning processes have been incorporated into our repository to create value and share knowledge across the company. Moving into a zero-carbon policies scenario, this secondment experience is helping us to advise our clients on how to track and improve their performance to become sustainable communities."

Andrea Imaz, Senior Urban Designer, Perkins+Will

Informing the 'Digital Blueprint' for the Houses of Parliament

Colin Williams, Houses of Parliament and Dr Jennifer Schooling, Director of CSIC

This ongoing project will support the development of the 'Digital Blueprint' for the management of the Parliamentary Estate and will use both the asset management and the asset monitoring work of CSIC. Results will include a digital blueprint of the Estate and outline the digital handover process.

"Working with CSIC has been invaluable in providing an industry insight into our strategy for the digital transformation within the Parliamentary Estate. UK Parliament is keen to understand and keep an eye on the future and engage with industry and stay aligned with initiatives such as the National Digital Twin Programme developed by the Centre for Digital Built Britain (CDBB). We recognise we must become an informed client and show leadership in the area of digital transformation and become an exemplar asset owner and a beacon for others to follow."

Colin Williams, Head of Digital Asset Management, the Houses of Parliament

Applications of new techniques to the detection and monitoring of bridge scour

Graham Webb, WSP and Professor Cam Middleton

This secondment is focused on the practical application of satellite data-based synthetic aperture radar (SAR) interferometry (InSAR) and other promising techniques on the specific problem of managing risks due to bridge scour, combining the practical experience of WSP with the latest developments emerging from CSIC, Laing O'Rourke Centre for Construction Engineering and Technology and other research groups. This project will produce a guidance document for asset owners, operators and maintainers on the use of new monitoring technologies in relation to bridge scour.

"Scour is the single biggest cause of bridge collapses but is difficult to detect, mainly relying on periodic visual inspections by divers. This secondment provided an understanding of the capabilities of emerging satellite-based and vibration-based monitoring techniques. There is no 'one size fits all' approach to monitoring structures, but these techniques will be a valuable addition to the tools available to asset managers and I am keen to look for further opportunities to trial them."

Graham Webb, Principal Engineer, WSP

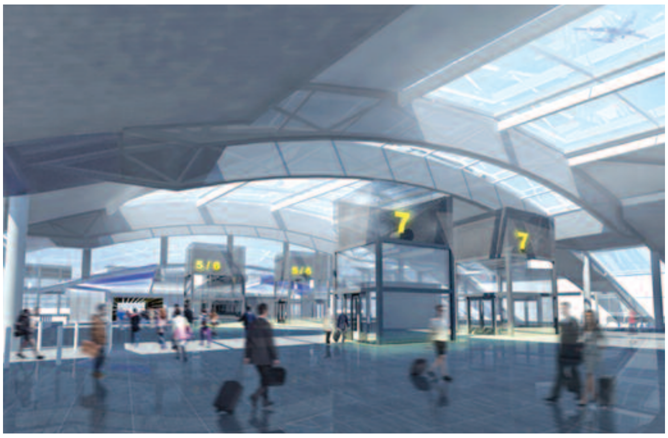


Image: Costain

Gatwick Airport Station

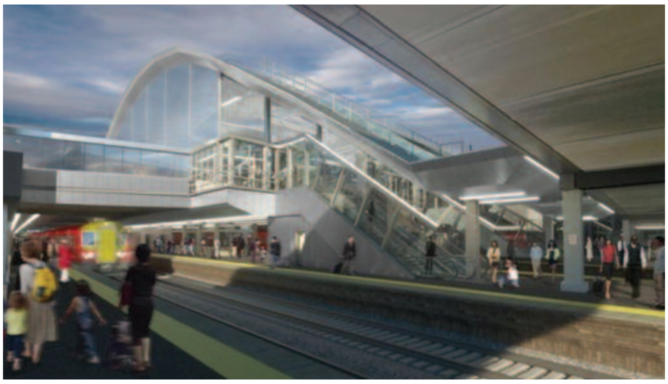


Image: Costain

Designing in data insights to improve customer experience at Gatwick Airport Station Upgrade

Dan Rennison, Costain and Dr Jennifer Schooling, Director of CSIC

Network Rail is improving capacity at Gatwick Airport Station using integrated learning and better use of data from CSIC research outcomes to create a train station that improves customer experience. Costain is the main contractor with the responsibility for the design and build of the station. New insights gained from data and extended research will have impact on the future development and plans. This secondment will develop an industry guide and process that can be used in the commercial discussions between the client, contractor and the design partner to embed the learning from CSIC into the creation and modification of new infrastructure.

"The secondment is allowing the exchange of knowledge between industry, Costain and CSIC into new multi-million-pound investments such as the Gatwick Airport Station Upgrade project for Network Rail. Through the secondment we will deliver the possibility of trialling and incorporating pioneering technology and digital processes developed from CSIC research. This research can be implemented into the delivery of the works at different project stages, assisting innovation transfer and the creation of added value services in the delivery of UK infrastructure whilst increasing outcomes for Gatwick Station."

Dan Rennison, Head of Data Insight, Costain

MEMS surface gravimeter for geotechnical surveying

Guillermo Sobreviela-Falces, Silicon Microgravity Ltd and Professor Ashwin A Seshia

This project aims to investigate packaging techniques for Micro-Electro Mechanical Systems (MEMS) accelerometer chips, essential to addressing device drift due to temperature and other environmental effects, to provide long-term stability. The National Research Facility for Infrastructure Sensing, in the new Civil Engineering Building, provides capability for the testing, characterisation and packaging of MEMS sensors. Prototypes are being developed in conjunction with a programme involving Silicon Microgravity and the University of Birmingham, and suitable prototypes will be field tested as part of this project once packaging techniques are developed.

"Collaboration with CSIC has allowed Silicon Microgravity (SMG) to accelerate the de-risking of our current breakthough MEMS surface gravimeter sensor developments, leading to improved sensors and new options for geotechnical surveying. It has enabled access to university expertise as well as leading-edge equipment for this phase of the project. SMG has been able to interact with CSIC geotechnical end-users more specifically about the future applications and variety of infrastructure requirements for improved geotechnical surveying. This feedback is critical to positioning the development of the sensors. At this point of the project the MEMS surface gravimeter is being tested in a low-noise environment and its practical behaviour followed by field evaluation."

Guillermo Sobreviela-Falces, MEMS Design Engineer, Silicon Microgravity Ltd

Photogrammetric study of landslides and rapid ground deformation

Xuanyu Zhao and Shirley Ong, Cam Dragon Corporation Ltd and Dr Dongfang Liang

The potential of photogrammetry, deploying multiple synchronised cameras, to capture the fast development of landslides and other rapidly-changing ground surfaces is the focus of this secondment. Multiple still images corresponding to the shape of the object of interest at a particular instant are used to reconstruct the three-dimensional shape which can then be computed by Structure From Motion (SFM) algorithms. The aim is to develop a low-cost, versatile three-dimensional reconstruction system capable of capturing the ground surface shape and changes over time to enable better understanding of the development of landslides.

"Participating in the secondment programme with CSIC has enabled us to learn the latest photogrammetric technologies, which is an opportunity we wouldn't have had in our normal work. The secondment rapidly connects the laboratory research to the industrial solution, and it lays down the foundation for the continued collaboration between CamDragon and the University of Cambridge."

Shirley Ong, Senior Consultant, Cam Dragon Corporation Ltd

The strong floor slab instrumented with fibre optic sensors at the new Civil Engineering Building

Image: Epsimon Ltd

Smart infrastructure: Data from real performance to enable better decision-making to reduce carbon, increase resilience, and preserve resources.

Engaging with the challenges of mitigating and responding to climate change is crucial; the decisions we make today are key to ensuring a safe and sustainable world for everyone, both now and in the future.

Our infrastructure must be sustainable as well as sustained. Innovation in monitoring, data collection and curation, and the associated analysis provides insights and valuable tools to address industry challenges by supporting resource and carbon-efficient design, construction, operation, maintenance and integration of infrastructure and the built environment.

The following case studies focus on the use of data and smart infrastructure solutions as tools to enable better decision-making and help to transform infrastructure and construction.

The heat is on: a data-driven framework to better target domestic energy policies

Decarbonising domestic heating

The domestic sector in the UK is responsible for more than a quarter of total energy consumption and greenhouse gas emissions, surpassing all other sectors including road transport and industry[1, 2]. Government commitment to reducing carbon dioxide emissions by 80 per cent by 2050 requires effective policy to address domestic energy use.

Decarbonising domestic heating constitutes an essential part of the full path to achieve the 2050 goal, and a range of national government policies and initiatives have been introduced over the years with varying degrees of success. Promotion and implementation of these national policies has fallen to local authorities.

While most cities in the UK have reduced emissions per capita, there is a large variation of domestic gas consumption (the primary fuel used to heat homes in the UK) both within and across cities; compared to the bottom 10 per cent, the top 10 per cent of households consume at least three times more gas[3]. Successful implementation of energy policies is only possible if the range of consumer needs and behaviours are understood. Knowledge of the nature of these variations is an essential step for effective design and implementation of policies that regulate newly built homes and encourage households to improve energy efficiency of existing homes.

Contributing factors to gas consumption

Research to date suggests the variations are as much a result of the built environment as of wider socio-economic-demographic features of the household, but their combined influence on variations of residential heating consumption is not well understood. Exploring the interaction between the numerous contributing factors to the different levels of consumption brings increased insight and additional information that can support local authorities to deliver more efficient policy aligned to securing carbon zero.

A data-driven framework

The UK government, local authorities and public bodies publish a wide-ranging and high-quality collection of datasets available to the public. CSIC researchers are working in collaboration with The Alan Turing Institute to take a data-driven approach using statistical clustering to optimise the use of these datasets to support more effective urban energy policy and better decision-making. Using this approach helps to identify similarities between a number of local authorities suggesting the possibility of increasing efficiency by collaborating to share knowledge, promote policy and allocate resources.

CSIC researchers collected all available public data at urban analysis level to gain as much information as possible about domestic heating across different local authority areas in London. Rather than solely focusing on gas consumption levels, unsupervised machine learning algorithms were applied to create clusters of gas consumption-related information. Crucially, the characteristics of the data at each level were matched to the most suitable clustering algorithm.

A two-step clustering framework was selected because the highest resolution of available data are usually at a different scale from the more aggregated scales at which policies are executed. Residential gas consumption data is available in the UK at the Lower Super Output Area (LSOA) level (uniformly constructed data from the national census). CSIC researchers were able to preserve the more detailed and accurate information contained at this level and aggregate the outcomes to be relevant for understanding variations of gas consumption across different Local Authority Districts (LAD). The two-step framework comprises LSOA-level and LAD policy-level data enabling executive bodies to focus on a range of results according to stakeholder interest. In addition, the framework enables both a numerical and spatial analysis without directly including the target variable and geographical information in the modelling process. The multi-layered approach applies different algorithms to result in more insights into urban energy consumption.

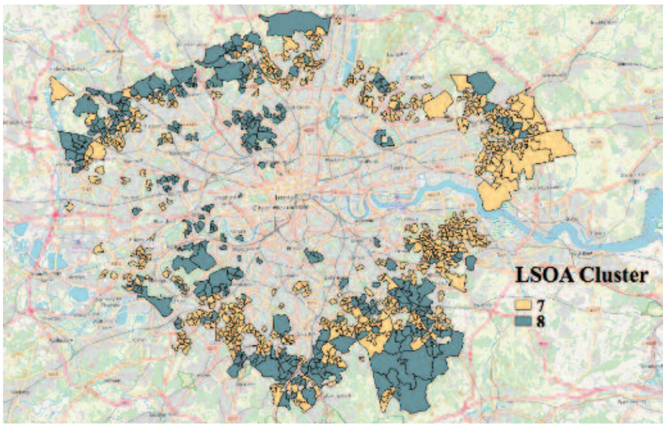
Variables affecting gas consumption

The clustering framework was used to analyse the variations of residential gas consumption across the different LADs. A total of 18 variables related to domestic gas consumption were collated including residential energy consumption, built-environment features, and social-economic and demographic data of the Greater London Area (home ownership; employment status; ages of occupants; health of occupants; median income; and type of house); domestic gas consumption information is not directly included in the clustering process. Except for the built environment and energy-efficiency ratings, all other data were collected in 2011. Traditional approaches to analysing variables affecting domestic gas consumption tend to prioritise the quality of the dwelling whereas the inclusion of LSOA data in the framework enables a wider and richer range of socio-demographic and locational constraints affecting residential energy demand to be identified. This framework not only invites comparison between buildings but also between local authority areas.

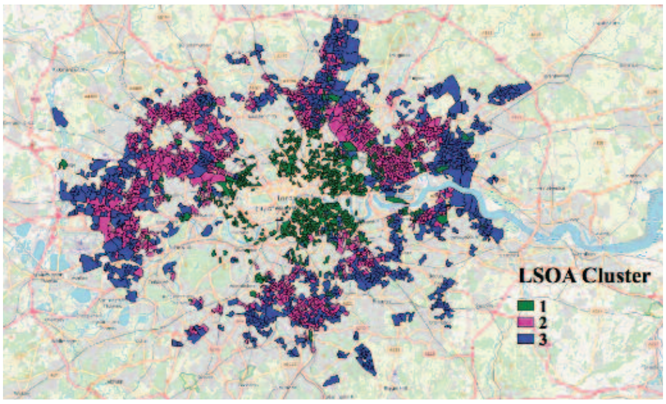
> “Through statistical clustering, we have identified plausible energy demand patterns, and probabilistically grouped households where the same combination of features explain consumption. Unlike regression models, clustering provides a more integrated view by taking all the diverse but relevant information into account at the same time. In cluster analysis, correlated variables only strengthen the identification of patterns (similarities) towards certain directions, which is a reflection of real-world conditions.
>
> Dr Ruchi Choudhary, Data-Centric Engineering Group Leader at The Alan Turing Institute and CSIC Investigator

[1] J. Palmer, I. Cooper, United kingdom housing energy fact file 2013, Department of Energy & Climate Change, Prepared under contract to DECC by Cambridge Architectural Research, Eclipse Research Consultants and Cambridge Energy. The views expressed are not necessarily DECC's p172 (2013).
[2] BEIS, Energy Consumption in the UK (ECUK) 1970 to 2018, 2019.
[3] J. Morley, M. Hazas, The significance of difference: Understanding variation in household energy consumption.

Spatial distribution of clusters



(a) high consumption level clusters



(b) low consumption level clusters

Eight clusters were generated showing differences in levels of gas consumption (as an example, clusters 1, 2, 3, 7, and 8 are shown above). In clusters indicating similar levels of gas consumption the framework identified a range of spatially and numerically different variables suggesting various drivers behind the level of consumption. For example, among low consumption clusters the unemployment rate, housing stock energy efficiency and household composition can be significantly different.

Informing policy

Taking a data-driven approach enables domestic gas consumption to be explored in much greater detail. The framework provides an application showing how to work with a range of data and match the machine learning algorithm to urban scale problems which can be adopted by local authorities. Generating richer information enables better decision-making to address specific challenges related to levels of consumption and to target policy accordingly.

Next step

The framework shows relationships and similarities between local authorities in relation to domestic gas consumption suggesting the possibility of sharing information to make best use of resources. The framework could be extended nationwide and adapted for urban analysis of other topics such as identifying communities that can be transitioned to zero carbon more easily than others.

Applying this data-driven approach in India

Slipping through the net: targeting energy poverty interventions in India

Lack of access to clean fuels in fast growing cities in India poses risks to health, the environment, and livelihoods, with many households still reliant on solid biomass fuels to meet some or all of their energy needs. Policies to promote the uptake of clean fuels are often national in scope with a focus on cost, and not targeted to the needs of local communities. Modelling of residential energy trends in India, and definitions of energy poverty, have usually been based on income. However, many of the challenges in accessing and adopting cleaner fuels are influenced by a combination of non-income factors.

Households can follow different pathways in transitioning to clean fuels and these pathways feature different challenges and barriers that must be overcome. For example, labourers may struggle to save their daily wages to make the monthly gas canister payment, whereas households in informal settlements may be unable to benefit from subsidies intended for them due to land tenure issues. Identifying such transition pathways in India is made difficult by data scarcity and lack of appropriate analytical approaches.

CSIC researchers, in collaboration with the Indian Institute for Human Settlements (IIHS) in Bangalore, carried out a targeted survey of 2100 low-income households in five cities across the south Indian states of Karnataka, Tamil Nadu, and Kerala. A data-driven approach was used to identify the different clean cooking transition pathways amongst low-income households, combining both socio-economic and demographic data with in-depth interviews. A two-step clustering method allowed for additional information to be gained from the data by cross referencing the findings from the interviews and survey data to reveal patterns not otherwise identifiable.

In Bangalore four different transition pathways were identified, each with its own unique policy challenge. Using these pathway definitions from the rich dataset researchers are developing a model for a decision support tool which can use publicly available data to identify the likely transition pathways in a given ward and highlight the associated policy issues so as to target interventions to address these.

A kitchen of a typical low-income household in Kochi, Kerala, with both a biomass 'chulha' stove (on right) and a government subsidised dual burner gas stove (on left)

Contact: CSIC Investigator Dr Ruchi Choudhary
Team: Dr Ruchi Choudhary, Mingda Yuan, André Paul Neto-Bradley

New use for existing technology to identify potential sinkholes

The occurrence of sinkholes during construction can have devastating consequences. The development of an early warning system to predict early formation of sinkholes before they caused property damage or even loss of life would be of huge benefit to the infrastructure and construction industry. "We know the areas they are likely to occur but sinkhole events are impossible to predict because there are so many different processes that can cause them," said Dr Helen Reeves, British Geological Survey.

Conditions for sinkhole formation

Sinkholes can best be described as a depression or hole in the ground caused by the collapse of the surface layer into a subterranean void. These can be caused by different events including the collapse of underground mine workings or the dissolution of salt deposits or soluble rocks including limestone, chalk, gypsum and dolomite, all of which are widespread across the UK.

Sinkhole formation can be triggered by changes in drainage conditions, for example natural flooding or leaking or burst water pipes, which accelerate the formation of the underground voids until the surface can no longer support itself and it collapses.

Changes in land use, such as construction and development, can place additional loading above an existing void and result in the collapse of otherwise stable ground. The most dangerous types of sinkholes are those that form without any apparent warning causing catastrophic damage to infrastructure and potential loss of life.

Sinkholes and construction

Often in the development of transportation networks, for example road and railways, the infrastructure is required to cross geotechnically challenging areas such as karstic environments or undermined areas. It is not always technically feasible or economically viable for these problematic void-forming areas to be avoided. A timely example includes the current development of the HS2 network where the presence of deep salt karst and shallow mining along part of the route has been identified as technically challenging for its design and construction. In such cases as these, it would be advantageous to the infrastructure owner to have detailed monitoring of ground conditions to provide an early warning of sinkhole development by identifying the accumulation of settlements at either the surface or within the supporting ground layers. This would allow early intervention such as filling the growing void or closing off the sinkhole risk area prior to collapse.

Despite an increased interest in this phenomenon, there is no robust method yet available capable of monitoring a large area and providing early warning of the development of sinkholes.

Testing the use of fibre optic monitoring for early warning of sinkhole formation

The incorporation of fibre optic cables into earthworks could provide an opportunity for significantly improved information on the location, mechanisms and magnitude of ground movements in real time. The potential to monitor tens of kilometres with a single fibre optic cable and obtain distributed readings every metre makes this an ideal technology for development of an early warning system for surface or near-surface settlement as a result of the formation of subterranean voids. These cables are robust and can be buried into the earthworks during the construction of the infrastructure providing a long-term monitoring solution.

CSIC conducted laboratory testing to determine the potential for the use of fibre optic cables laid in the ground to locate potential sinkholes as they are developing. This investigation was made possible using the newly acquired Luna ODiSI (Optical Distributed Sensor Interrogator) 6100 which allows for the monitoring of fibre optic cables with an incredibly high spatial resolution of less than 2.6mm. Previous analysers used for distributed monitoring of fibre optic cables allowed a minimum resolution of 500mm which is too large for typical laboratory testing.

The laboratory testing was performed at the Schofield Centre at the University of Cambridge, and involved using a small-scale model which included a trapdoor to simulate the formation of the sinkhole. Fibre optic cables were laid on the soil at various heights above the trapdoor. The model included a Perspex window which allowed photographs of the soil movement to be taken. The photographs were analysed using particle image velocimetry to calculate the soil displacement and strain, and correlate this to the recorded strain in the fibre optic cables.

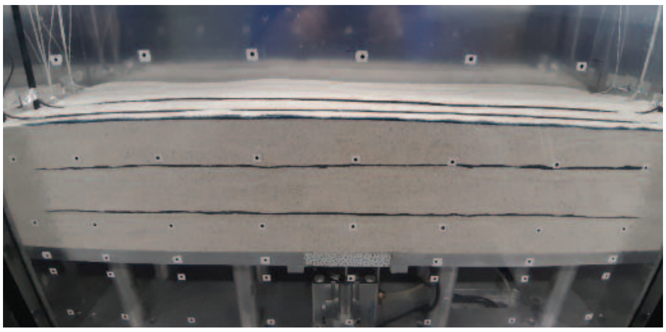


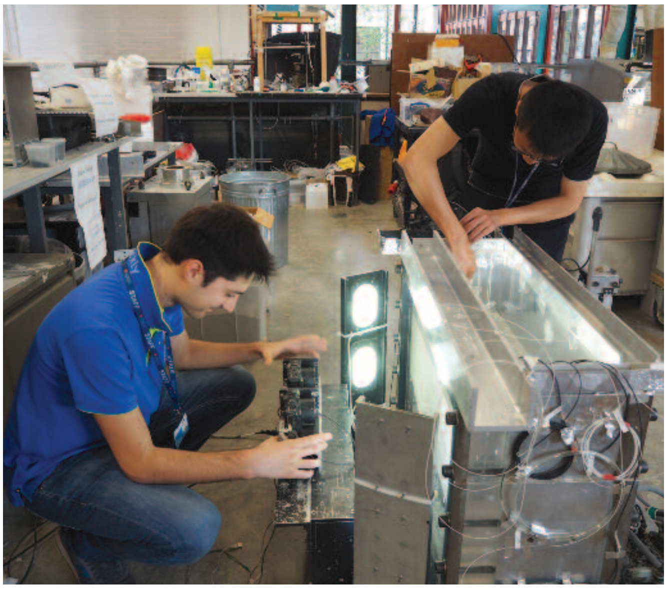
Image: Gianluigi Della Ragione

Fibre optic cables being laid during the formation of the sand bed to monitor the strain developed in the soil as a result of the formation of a sinkhole, simulated by lowering a trapdoor. The black sand layers indicate the levels of the cables in the soil

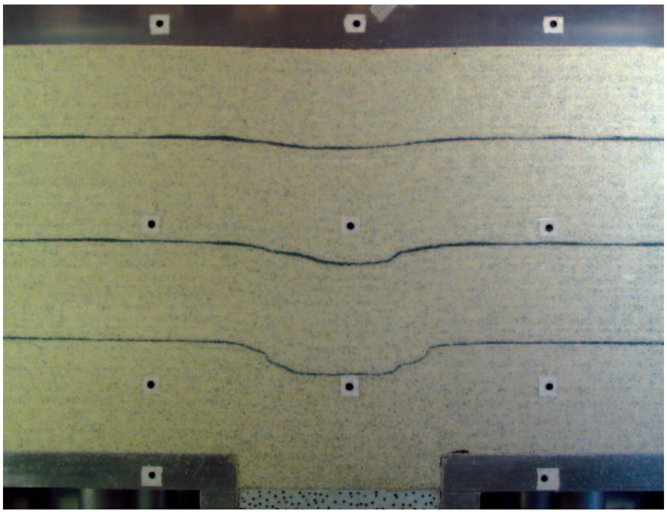
> Our objective is to prove the feasibility of using a fibre optic sensing system to detect zones of subsidence in the soil that could potentially damage infrastructure and cause loss of lives. Our team is making promising progress towards identifying a signal signature that could help locate and mitigate this type of natural disaster.

Dr Christelle Abadie, Lecturer in Civil Engineering, University of Cambridge

Image: Dr Christelle Abadie



Gianluigi Della Ragione (CSIC Summer Intern 2019) and Dr Xiaomin Xu (CSIC Research Associate) preparing the test set-up



Completed 'sinkhole' formation showing the movement of the soil

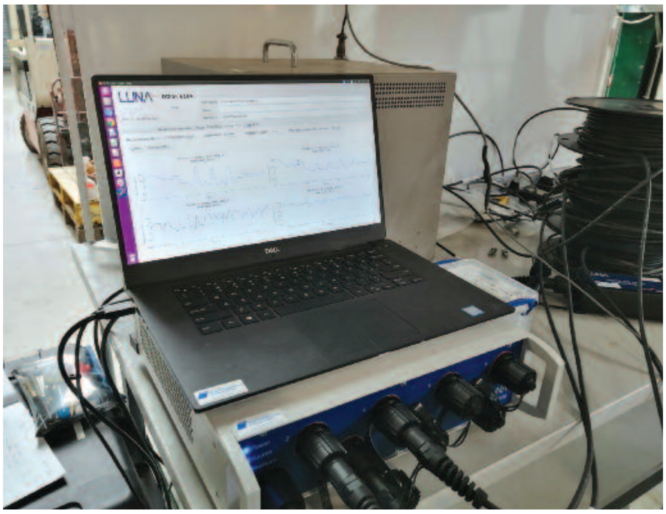
Challenges in interpretation of the data

Careful interpretation of the obtained strain signatures is crucial for the retrieval of the localised ground displacement field with high precision, together with deeper understanding and prediction of the ground deformation and collapse mechanisms. The relationship between the longitudinal strain profile measured by the distributed fibre optic sensing (DFOS) cable and the ground displacement profile would depend on a number of factors, including DFOS cable-soil interfacial behaviour, the size and depth of the sinkhole, the vertical displacement induced, as well as the environmental disturbance. The testing aimed to investigate these in a controlled manner.

Results and next steps

Preliminary results show the formation of a clear strain signature both in the ground close to the 'sinkhole' and closer to the surface. This signature is evident even with very small movements of the sinkhole. Clear patterns of movement are formed in the soil which correlate well to the measured strain from the cables. This shows the strong potential for fibre optic technology to be used as a sensor for small ground movements and to give an indication of where potential voids are being formed. Further detailed analysis is required to give more robust correlations of the sinkhole size and location to the strain pattern observed in the fibre optic cable.

Early warning systems can provide a distinct advantage in allowing timely action to prevent catastrophic collapse; such interventions are far more economical than the cost of dealing with disasters, and are potentially life-saving. The incorporation of a DFOS-based sinkhole detection system during major construction projects, such as demonstrated here, would significantly reduce costs and increase knowledge of where sinkholes might appear.



Testing with the LUNA ODiSI in progess with the cables recording strain as the sinkhole is developed at the base of the box

Contact: CSIC Investigator Dr Christelle Abadie
Team: Dr Christelle Abadie, Dr Xiaomin Xu and Dr Talia da Silva Burke. Testing was conducted by Gianluigi Della Ragione, CSIC Summer Intern 2019, and Tobias Moller, Department of Engineering 4th year student

Line of sight: an asset management methodology to support organisational objectives

Organisations responsible for infrastructure assets must understand the importance that asset information has to achieving their organisational objectives. Despite the potential benefits of effective information management to optimise digital opportunity, many organisations still struggle to identify what information should be collected to support the efficient management of assets throughout their whole life. Asset-related information not collected in alignment to organisational requirements can restrict the performance of capital investment decisions, risk management and operational performance throughout the whole life of the asset and ultimately impact productivity.

Standards such as the PAS 1192 series and ISO 19650 describe the approach that organisations should take to define their asset information requirements (AIR) and the asset information model (AIM). The AIR should be informed by the organisational information requirements (OIR), which in turn is defined based on organisation objectives. However, the standards do not prescribe how this should be achieved and what processes should be used.

CSIC researchers have developed a top-down methodology that supports the development of AIR in relation to OIR and addresses the disconnect between the PAS/ISO BIM-related standards and asset management standard ISO 55000. The novel aspect of this approach is the development of Functional Information Requirements (FIR) to bridge the gap between the OIR and the AIR. This is achieved by identifying and understanding the 'functions' of the asset systems that help address or have an impact on the OIR, to then identify the assets that form each function.

Industry collaboration to test the value of the asset management framework

The methodology is currently being tested within industry as part of a CSIC secondment project with a member of the Asset Management Team from CSIC Industry Partner, Jacobs. The Asset Management Team is supporting Network Rail in delivering the Transpennine Route Upgrade (TRU) – a major railway enhancement to improve connectivity between York and Manchester. TRU involves upgrading existing assets and installation of new assets to deliver a railway that will leave a lasting legacy. Exploring the benefits, challenges and opportunities of the methodology for Network Rail facilitates the longer-term possibility for a digital twin of the TRU, which would require whole-life data collection and management from the starting point of the programme and throughout design, construction, operation and integration.

Application tool to identify organisational objectives

A wide range of Network Rail strategic documents were collated to identify organisational objectives. In order to reduce time required to read large volumes of text, an algorithm-based tool using data-mining techniques was developed to search the text and identify locations of organisational objectives. More than 60 objectives were sense checked and put into the following categories: operational; reputational; customer; financial; environmental; and health and safety. For the purpose of testing the methodology within the secondment timeframe of four months, one organisational objective was selected: improve customer satisfaction.

The top-down methodology creates a two-way line of sight from organisational objectives to asset requirements with functional requirements located between the two. A sample of FIR and AIR aligned to the identified organisational objective was captured. This approach helped deconstruct siloed structures familiar to many organisations and enables a systems perspective.

A seven-step process provides a rigorous methodology and holistic approach capturing interfaces between asset disciplines and types – see the framework opposite. The methodology clarifies why an organisation needs specific asset information, which ensures data collected has a clear purpose making it possible to optimise value. Being able to classify data is particularly helpful in the context of the UK government's commitment to achieving net-zero carbon emissions by 2050 making the carbon cost of data a consideration. It also enables classification and curation of data throughout the whole life of the asset, making data accessible to any asset manager and operator. Establishing a 'golden thread' of valued information offers insight, it enables better decision-making and safeguards an organisation against the consequences of bad decisions.

Identifying value to Network Rail

A series of workshops were organised for a number of senior Network Rail representatives to explore the methodology, test the framework and identify its value in relation to the TRU Programme and Network Rail. To ensure the framework's user accessibility and avoid the necessity of referring to spreadsheets of information, CSIC and Jacobs developed a web app streamlining the three-layer framework process. The web app helped record information requirements during the workshop and was developed with a view to being used throughout Network Rail's TRU upgrade programme, and potentially be applied to future projects and programmes. Feedback about the framework from attendees was very positive and recognised the added value and business case to Network Rail from curating data for future use and whole-life operation. Network Rail recognised the potential value of applying an information management framework to support organisational objectives.

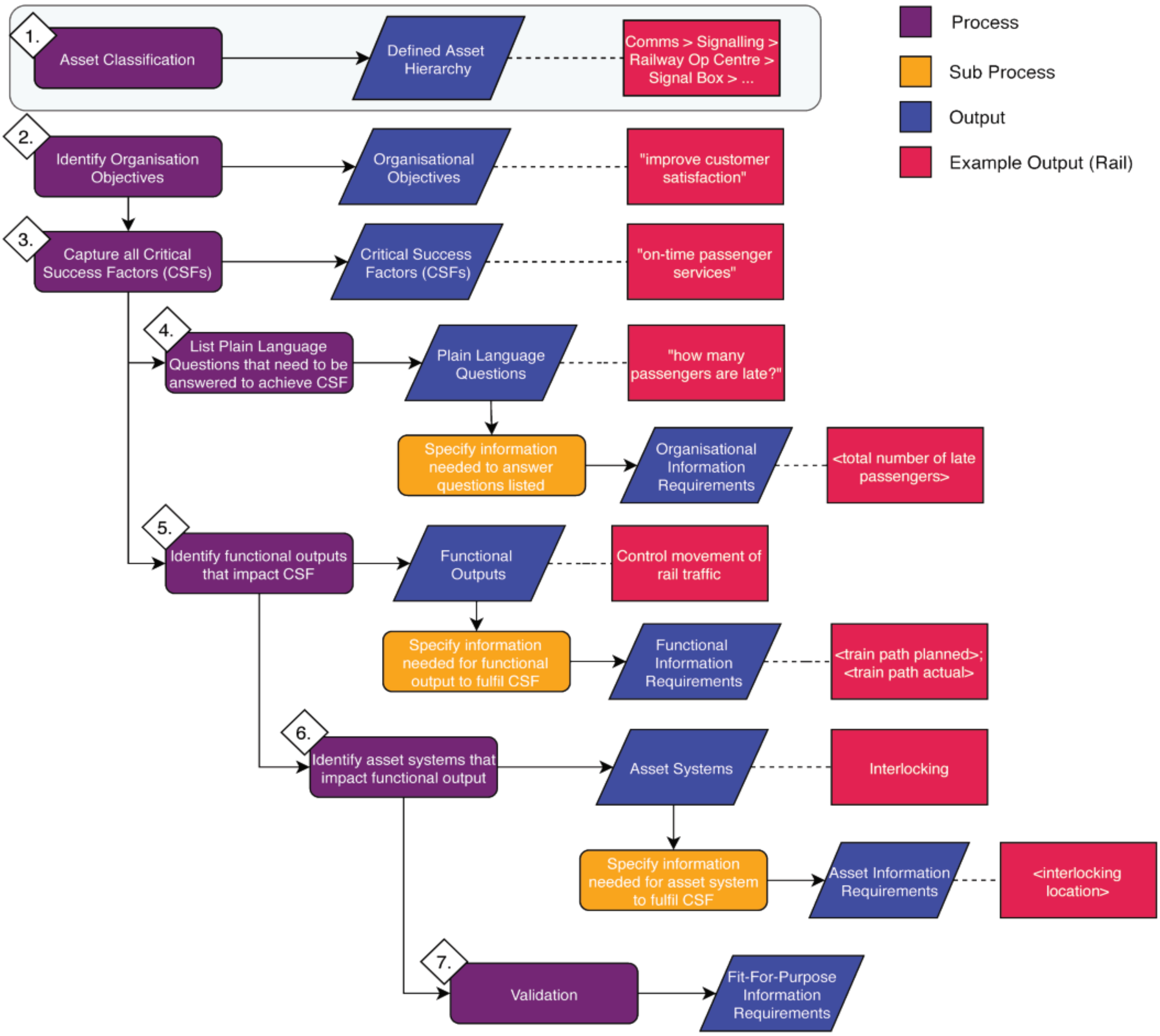
Challenges and opportunities

While applying this methodology to an organisation's entire asset estate requires considerable investment of time and related costs, the potential benefits of this framework are considerable and include long-term yield. The flexibility of the methodology makes it suitable to apply to a single project, such as the TRU programme, or at scale. The process brings wider benefits that prepare an organisation to be well positioned to optimise opportunities presented by digitalisation. Organisations without adequate data and information management will be left behind.

This CSIC and Jacobs secondment has resulted in an information management framework that is both useful for and usable by industry.

> "Network Rail should implement this method or similar now as there is a lot of data currently not being captured effectively that should be.
>
> Penny Robinson, Programme Change Manager, Network Rail

The framework



Key benefits of the framework

Benefits of applying this methodology include:

- Identifying gaps in information capture
- Establishing line of sight from asset information to organisational objectives
- Providing holistic process capturing interfaces between asset disciplines/types
- Allowing better decision-making to optimise performance and manage risk throughout the whole life of the asset.

In addition, two applications have been created as part of the secondment project which can be used by all collaborating partners – Jacobs, Network Rail and CSIC – on future projects.

Our infrastructure assets are required to give service over a long period of time and existing assets form the greatest part of the UK's total infrastructure; each year in this country we add just 0.5 per cent to the capital value of the assets we have inherited[1]. Having a line of sight from asset information to organisational objectives enables an organisation to be agile if circumstances, such as extreme weather events and the consequences of climate change, require organisational objectives to change.

Contact: CSIC Investigator Dr Ajith Parlikad
Secondment: Aaron Johnson, Senior Asset Management Consultant, Jacobs
Team: Dr Ajith Parlikad, Dr Jennifer Schooling, James Heaton

[1] Smart Infrastructure: Getting more from strategic assets, CSIC and industry partners, June 2017

Monitoring of under-reamed piles during tunnelling interception using distributed fibre optic sensing

The Transport for London Bank Station Capacity Upgrade (BSCU) project is reconstructing one of the busiest interchanges on the London Underground network. The tunnelling and underground excavation works commenced in 2016 and excavated their way around a 'rabbit warren' of existing tunnels and beneath many significant buildings in the City of London. An extensive instrumentation and monitoring programme was established to safeguard existing infrastructure assets and buildings.

The unprecedented pile interceptions required at the Princes Court building won the 2019 BGA Fleming Award. This eight-storey two-level basement building, owned by The Worshipful Company of Grocers, was built in the 1970s and is supported on 25 large diameter unreinforced under-reamed piles in London Clay. The sprayed concrete lining (SCL) tunnelling fully intercepted four under-reamed piles. The interception strategy involved cutting piles just below tunnel crown and, while temporarily unsupported, constructing a reinforced concrete permanent load transfer structure around the tunnel for each pile. Fibre optic monitoring was installed in existing piles to measure pile response due to tunnelling and interception and to enable verification of design assumptions.

Innovation and collaboration

Working with Dragados, an Abaqus 3D finite element (FE) geotechnical substructure model, which included the under-ream piles, raft slab, building basement and all tunnel excavation sequences was created by consultant Dr Ali Nasekhian and team at Dr Sauer & Partners Ltd. This model was coupled with a Strand7 3D super-structure model from Robert Bird Group to predict pile foundation and building response to staged tunnelling excavation.

At basement slab level, the tops of the under-reamed piles were instrumented with settlement monitoring studs fixed into the concrete slab above each pile position. At tunnelling level, reflective monitoring targets were installed on the pile shafts above and below the cut level as soon as the pile shaft was exposed (Figure 1). This conventional type of monitoring of the intercepted piles before and after cutting recorded the top and bottom pile displacement from exposing the pile, but not the pre-exposure displacement of the base of the pile nor the response down the length of the pile.

To fully capture pile behaviour due to tunnelling and interception, distributed fibre optic sensors (DFOS) were used to measure the axial strain over the length of the piles during interception and other construction activities. The use of fibre optics to measure strain in new piled foundations is a well-established method and transferring this to the monitoring of existing piles has proven successful. It is the least invasive and only viable method for spatially continuous axial strain measurement where access is limited.

CSIC was brought in by the project team as experts in this field and applied this method by inserting fibre optic sensing cables into two of the 50-year-old under-reamed piles (one intercepted pile and one non-intercepted pile). The piles were cored at 100mm diameter from basement level to depths of 18.9m and 25.3m respectively. A temperature and a strain cable, pre-spliced to form two parallel lines, was lowered to the bottom of the pre-cored boreholes using a spherical weight to overcome buoyancy and keep the cables under tension when grouting (Figure 2). After installation, the cables were connected in a single circuit to a Brillouin Optical Time Domain Analysis (BOTDA) spectrum analyser located in the plant room of the basement.

Figure 1: Exposed under-ream pile prior to cutting (TfL)

Figure 2: Fibre optic sensing cables being lower into cored pile

> The innovative use of fibre optics to successfully verify modelling predictions of an unprecedented tunnelling pile interception again demonstrates the versatility of this technology in engineering.

Chris Barker, Associate Director at Arup. Technical Advisor to The Grocers

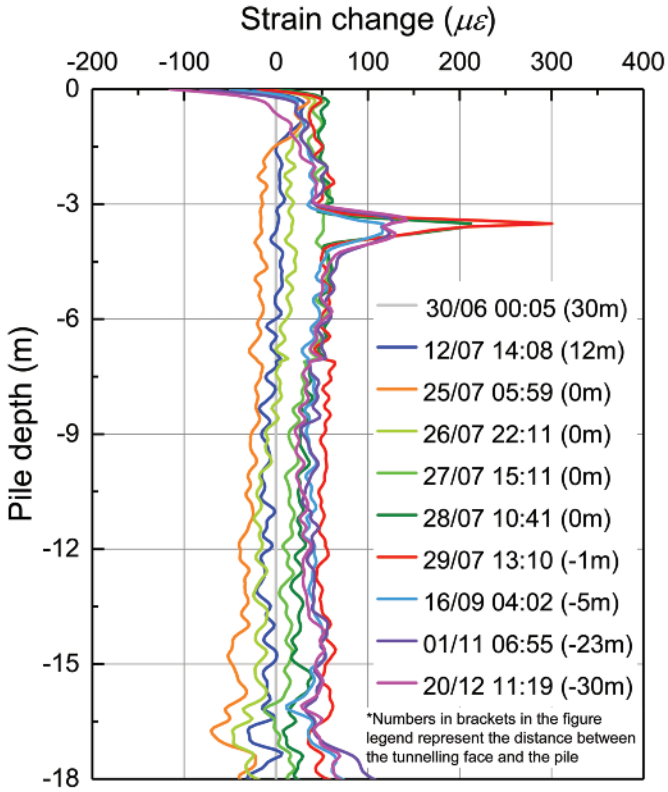


Figure 3: Strain profile during tunnelling and pile interception

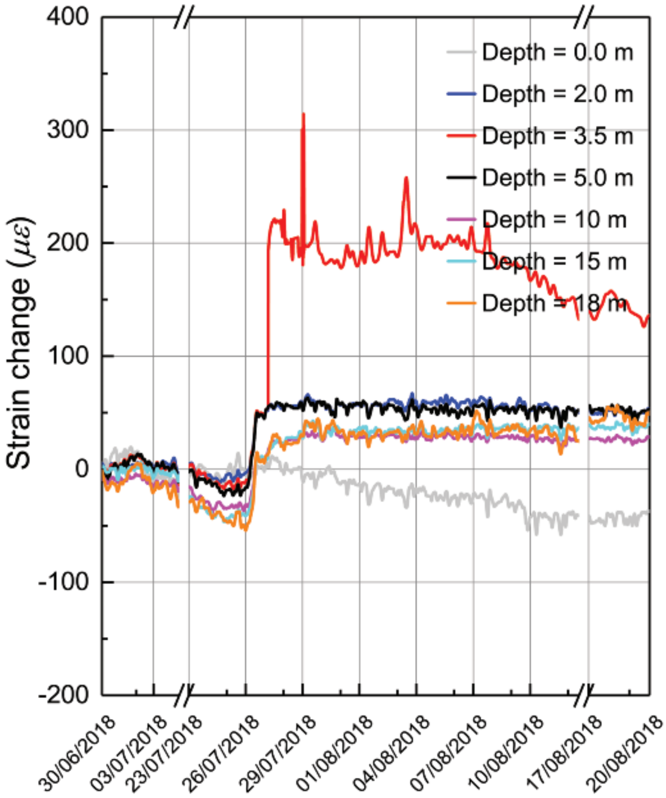


Figure 4: Strain changes at selected vertical locations in the pile

The under-reamed piles were monitored during tunnelling, pile interception/nibbling, support installation and post construction for over eight months in order to quantify the effect of these activities on pile performance.

The strain profiles and strain changes at selected vertical locations are presented in Figures 3 and 4, respectively, for one of the fully intercepted piles. There was little change in strain until the tunnel excavation reached the pile, at which point the axial strain increased all along the pile. This was followed by a sudden development of localised strain at the depth of 3.5m two days later. This localised strain had however halved within two weeks and is consistent with the presence of a short reinforcement cage down to this depth. The strain increase from pile interception to the load transfer structure completion measured an overall pile length extension of 1.3mm, which compared with 3 to 4mm measured by the conventional pile instrumentation.

Conclusion

This project may mark the first time this fibre optic monitoring method has been successfully used in piling interception during tunnelling. The conventional monitoring method would have been to measure the basement settlement at pile positions with studs, and measuring movement of the pile base by coring the pile and installing a rod extensometer. However, rod extensometers would only record displacement at discrete locations rather than at close intervals as with the fibre optics. It is not thought traditional instrumentation methods would have limited the pile interception solution, however more piles would likely have been instrumented and monitored. By installing innovative fibre optics and recording pile behaviour over the full pile length and at frequent time intervals, a clear picture of how the piles were responding to the advancing tunnel and pile interception gave much better confidence that the building was responding as predicted.

As our urban cities become even more connected with new infrastructure tunnels, there will likely be further opportunities for such smart fibre optic piles to provide a robust and reliable instrumentation monitoring method. There can also be ongoing benefit for such monitoring systems if it provides a means by which existing foundation structures can be reused.

The installation and use of fibre optic instrumentation to measure temperature and strain successfully verified the pile performance made in the design of the pile interceptions at Princes Court. Four of the Princes Court pile foundations are now permanently supported onto reinforced concrete load transfer structures around the new southbound Northern Line tunnel. Two of the 50-year-old piles retain the fibre optic instrumentation and have now become smart fibre optic piles which are available to inform future performance during multiple demolition and construction phases for the Princes Court site.

Contact: CSIC Senior Research Associate Dr Cedric Kechavarzi
CSIC team: Dr Cedric Kechavarzi, Dr Xiaomin Xu
Industry partners: Geocisa, Epsimon, Arup and Transport for London

Making sense: instrumentation and monitoring to support performance-based design

Efficient infrastructure will be of more value to its users and owners, will be more sustainable and can deliver better outcomes for society and the economy. Only through monitoring will we understand the real performance of our assets and be able to refine designs using data on actual performance, leading to reduction of carbon and the preservation of resources. More advanced sensors and data analysis will enable better product quality, enhanced construction safety and smarter asset management. CSIC is a leader in the field of smart infrastructure and data analysis solutions to enable performance-based design of resource-efficient structures.

Sensor systems informing asset design and management

The new Civil Engineering Building, located on the West Site of the University of Cambridge, which is home to CSIC and houses the UKCRIC National Research Facility for Infrastructure Sensing (NRFIS), (see page 41), has been instrumented with five sensor packages to monitor the whole-life performance of the asset. The sensor packages within the modular building create a live learning and research tool. Four of the packages comprise fibre optic sensing technology and were designed and installed by CSIC partner Epsimon Ltd.

CSIC investigators and researchers are developing technologies to store, interpret and visualise the data streams resulting from the sensor systems. This information will be used to monitor and understand the performance of the building components, assess performance against predictions made during design, and inform future design and modification to improve efficient use of materials and reduce embedded and operational carbon. This knowledge is intended to feed directly into the design and construction of future phases of the Engineering Department's expansion at the West Cambridge site, which will consist of a number of similar buildings.

Ground Source Heat Pump (GSHP) boreholes

• Temperature-sensing distributed fibre optic sensor (DFOS) loops in 2 GSHP boreholes 165m deep • Temperature-sensing DFOS loops in 1 sacrificial borehole 175m deep • Total of 1km of DFOS temperature-sensing cables

A distributed fibre optic temperature sensing system (DTS) is installed in two adjacent GSHP boreholes as well as in the ground between them. This system will provide the temperature profile along the depth of the boreholes and the ground, as heat is transferred to and from the building's GSHP system. The distributed temperature data will be used to assess the long-term performance of the GSHP system and feedback into its efficient operation. It will also allow the detection of possible long-term heat imbalance and associated system efficiency loss. The data will be used to calibrate heat transfer models and estimate the thermal properties of individual geological strata. This will help improve future system design by, for example, optimising the boreholes' depth, spacing and layout.

Strong floor slab

• 12 DFOS and 13 fibre Bragg grating (FBG) loops (top and bottom of slab) sensing strain and temperature • Total of 640m DFOS sensing cables and 319 FBG sensors • The strong floor is 20m long, 10m wide, 1m thick, weighing approximately 500 tons

A fibre optic sensor system in the post-tensioned reinforced concrete strong floor comprises two sub-systems, each installed in two layers, at the top and bottom of the slab: a distributed DFOS system, providing measurement of distributed strain and temperature, and an FBG sensor system, providing point measurements of dynamic strain and temperature at regular intervals (see Figure 1). The objective of this instrumentation is to enable strain measurement during construction and throughout the life of the strong floor, including: investigating immediate and long-term concrete creep caused by the post-tensioning; quantifying any loss of post-tensioning over the life of the structure thus informing the asset owner if, when and where re-tensioning needs to be carried out; and evaluating the effects of heavy, concentrated and dynamic loading during experiments carried out on the strong floor (see Figure 2).

Figure 1: The strong floor instrumented with DFOS and FBG sensors being concreted

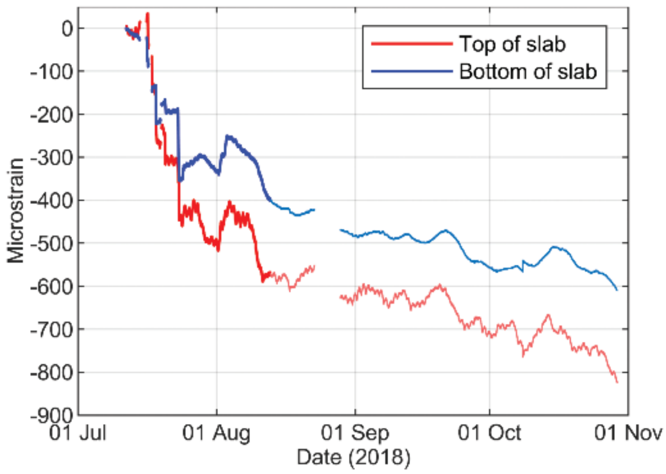


Figure 2: Compressive strain measured from two of the FBG sensors embedded in the strong floor: during (thicker lines) and after (thinner lines) post-tensioning of the slab

Basement raft and perimeter wall

• Two DFOS and two FBG loops installed in the raft (top and bottom of the raft), and seven FBG loops in the retaining walls sensing strain and temperature • Total of 120m DFOS sensing cables and 108 FBG sensors

A fibre optic sensor system is installed in the reinforced concrete raft at basement level (see Figure 3) and in the reinforced concrete walls around the perimeter of the basement, which lies beneath the strong floor. The system comprises two sub-systems installed in parallel: a DFOS system and FBG sensor system to enable the measurement of changes in strain and temperature along selected lines in the raft and walls. This is useful in order to observe the performance of the basement structure as a whole in response to the long-term effect of

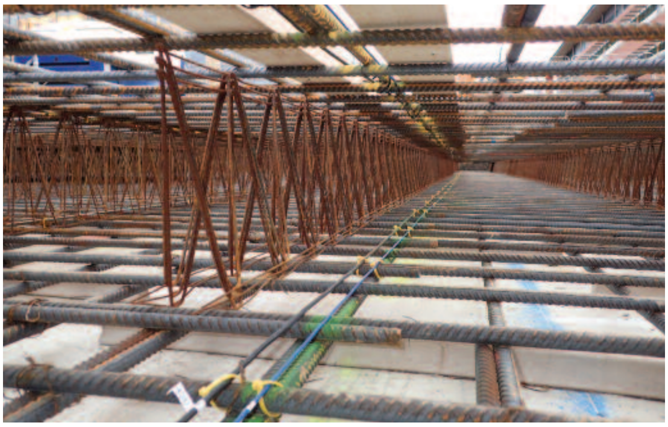


Image: Epsimon Ltd

Figure 3: Fibre optic sensor cables attached to the basement raft reinforcement

ground movement (heave on the raft and lateral pressure on the walls) and operational loading, such as when the strong floor above is being heavily or dynamically loaded.

Frame structure

• A complete frame comprising 12 columns and nine beams instrumented with one FBG sensor pair each (one sensor on each flange), to be monitored continuously • A total of 42 sensors comprising 66 FBGs

An FBG sensor system is installed on the steel structural frame of the building to provide dynamic strain measurement capability at point locations on all columns and beams along one entire cross-section of the structure. In total, 21 members are instrumented (12 columns and nine primary beams). The objective is to measure both static and dynamic axial and bending strain in the primary members of one representative cross-section of the structure. This can be used to monitor vibration and quantify strain (and therefore stress) in the primary structural elements to understand load distribution and structural performance under operational conditions. Providing evidence of structural behaviour could enable more efficient future reconfiguration or additions to the building over the long-term as well as enable the design of subsequent building extensions to be refined.

Blue roof

• Weather conditions, soil moisture content, water level and temperature sensors to assess the effectiveness of the blue roof, as well as providing environmental parameters for the other sensing packages

The building's blue roof (providing temporary storage and gradual release of rainwater) is being equipped with a monitoring system consisting of a weather station, 21 temperature probes installed in three vertical layers at seven locations, 24 soil moisture content sensors and seven water level sensors. The overall aim of the sensing system is to evaluate the effectiveness of the roof in regulating rainwater drainage runoff while supporting healthy vegetation growth and providing additional thermal insulation. By monitoring closely and continually the evolution of the temperature and water retention of the roof in relation to weather conditions, it will be possible to gain a better understanding of the environmental and ecological functions of the roof.

Making sense of sensing

Buildings are often perceived as static inanimate systems, but the potential of sensing and data analytics challenges this perception. Sensors embedded in the structure bring the building to life, making real the possibility of measuring structural health and performance throughout an asset's life.

CSIC is developing a set of tools to provide the means for measuring these vital signs, which are ingrained in the large continuous flux of data recorded by embedded sensors. These data management tools include an efficient data store, flexible communication protocols and modern software architecture, which in turn enable data analysis and data visualisation of the current state of the asset in real time. Among the opportunities presented by this new framework, two powerful features are the generation of knowledge for the performance-based design of buildings and engineering tools driving decision-making for asset management and maintenance.

The unprecedented amount of data acquired from the sensors embedded in the Civil Engineering Building can be used to compare the design models and guidelines with the actual building performance. This has the potential to yield upgrades of building design guidelines, underpinning a more cost-effective and sustainable construction industry. Moreover, a robust platform for real-time monitoring has the potential to radically change informed asset management decisions against the foreseeable challenges of the future.

Acknowledgement

The fibre optic instrumentation of the Civil Engineering Building was carried out in collaboration with Epsimon Ltd, which was responsible for the specification, design, and installation of the systems and for monitoring during construction.

> We still know surprisingly little about how buildings really work. This uncertainty results in excess material consumption being a default risk mitigation strategy – resulting in more carbon emissions. The installation of sensors on building components is the first step in a new and virtuous circle of learning that has the potential to shape the way we design future buildings. If, through measurement, we can determine the real demands that are placed on buildings, we can reduce uncertainty and improve future design methods.
>
> Dr John Orr, Lecturer in Concrete Studies, University of Cambridge

Contact: CSIC Research Associate Dr Nicky de Battista
Team: Dr Nicky de Battista, Dr Cedric Kechavarzi, Dr Miguel Bravo-Haro, Dr John Orr, Paul Fidler

Digital Cities for Change: testing a Cambridge city-scale digital twin for cross-disciplinary policy decision-making

Addressing the challenges inherent in delivering smart city systems requires a cross-disciplinary and systems approach. CSIC's Digital Cities for Change (DC2) project, funded by the Ove Arup Foundation, explores current city and infrastructure management structures and systems. It seeks to demonstrate how built environment data and digital tools can be used to inform better and more cohesive decision-making. DC2 aims to deepen understanding of how built environment data can help improve city planning, management and the delivery of public services.

Developing a new digital strategy with Smart Cambridge

CSIC has been working with Smart Cambridge, a programme led by Cambridgeshire County Council's Connecting Cambridgeshire initiative, supported by the Greater Cambridge Partnership (GCP), which includes Cambridge City Council, to develop a new digital strategy to support transport infrastructure investment and council policy goals to improve air quality and reduce congestion. The Cambridge City-scale Digital Twin (CDT) project (Phase 1 ran until August 2019 and was funded by the Centre for Digital Built Britain) focused on delivering a prototype model using existing data sources to demonstrate the value of a digital twin for facilitating cross-disciplinary collaboration in policy decision-making.

Outputs from the initial phase include: a socio-technical framework for investigating and supporting local digital development; a digital model prototype co-developed with local policy makers; two digital transformation scenarios regarding remote working and the use of electric vehicles (EVs) for demonstrating the value of digital twins as boundary objects and its potential policy use; and strategic links with local authorities, key technology providers and citizen groups.

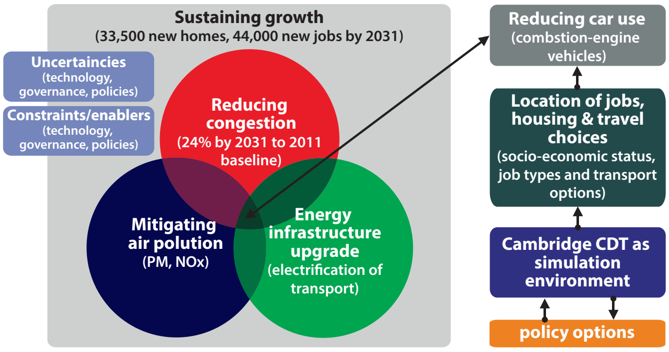
Between December 2019 and March 2020, a second phase of the project (funded by Innovate UK) saw researchers from the Smart Cambridge team working with CSIC as part of a secondment programme to further refine the digital model and test its value in a specific 'live experiment' with the Cambridge Biomedical Campus (CBC) – one of the designated strategic development sites in the city, with thousands of new jobs and homes set to be created in the area in the next decade.

Cambridge Biomedical Campus model to explore travel patterns

The CDT model has been extended using a large transport monitoring data set (Automatic Number Plate Recognition (ANPR)) to explore travel patterns to/from and around the CBC site. The extended model features a new algorithm for inferring the trip purpose and the potential socio-economic characteristics of car users according to anonymised vehicle trajectories. It also explores a cross-validation strategy through linking multi-source data. One key goal of the live experiment is to better understand how to constructively combine conventional data with emerging 'big data sets' to improve the quality of the model and the policy relevance of analytical outputs. The CBC experiment also involves further engagement with stakeholders and residents in the area in order to include their views and requirements in problem-framing for the CDT model.

The role of the Cambridge Digital Twin and new governance framework

The governance aspect of the Cambridge CDT projects focuses on understanding the social-organisational requirements – and the changes needed for example in terms of improved collaboration across organisational or professional silos – in order to ensure that



Objective and framework for the Cambridge City-scale Digital Twin

digital innovation contributes to improved city planning, management and the delivery of public services.

Organisational silos hinder joined-up policy making and implementation. They can also limit the ability to share data sets and, as such, reduce the availability of evidence to support decision-making.

The governance perspective highlights that innovating with digital tools makes important consideration of improving not only the 'quality' of the evidence (including the model itself and more accurate data and better algorithms) but also the processes of evidence provision and use in policy decision-making. Key considerations include improving the transparency of data-driven decision-making, allocating responsibilities and accountability for the decisions along this process, and allowing for participation of interested/affected parties.

Value and benefits

- The pilot projects and CBC experiment successfully demonstrated the value of a city-level digital twin and the policy insight it could generate to support more joined-up decision-making to achieve desired policy and practical goals
- The projects helped to highlight how technology development needs to take into account the social-organisational perspective to be able to reframe policy and practical goals into actionable strategic aims that digital innovation can help to address, and which contribute to improving governance processes and their outcomes for urban communities
- The early model created for this project was useful to the Smart Cambridge team to test various scenarios and it provides a strong platform from which they can scale up.

Looking ahead: underpinning data lays foundations for the ambition for a full digital twin

The local authorities in Cambridge are data-rich. Local councils, enabled by Smart Cambridge and GCP, are engaged with the technology community and investing actively in data collection schemes. These schemes have produced a large amount of data, the full value of which is still to be realised.

The major challenge for CDT is not simply the data it could generate or collate. Consideration of how data from different sectors and sources could be linked (technical), and how linking data could better support policy and practical interventions (governance) is essential, as well as keeping in mind potential unintended consequences (privacy, marginalisation). Without due diligence there is a risk that digital twins could be used simply to justify the presence of additional sensors and more siloed data in cities rather than delivering genuine public good.

Next step: Competency Framework

The CDT and CBC projects feed into the wider DC2 programme, contributing to development of a Competency Framework which will enable city managers to deliver better outcomes for their cities. Initial work on the Competency Framework began with unravelling the competency requirements and possible capability gaps needed to ensure the successful utilisation of the Cambridge CDT in policy decision-making. These investigations highlighted the importance of both technical (data literacy, data science) and procedural (communicating data-driven decision-making and enabling public participation) competencies. A draft Framework has been developed on the basis of the Cambridge projects which will be validated through other use cases (data driven solutions, digital tools) and city cases from within the UK and internationally.

> The Smart Cambridge programme explores how new and emerging technologies and data can be used to address some of the challenges that the city faces such as congestion, poor air quality and constraints on infrastructure such as energy. The collaboration with CSIC on digital twins brings cutting edge research out of academia and begins to apply it in the real-world. As part of this work we have co-created a number of prototype digital tools which have helped the programme to gain insight from data across domains. By combining data that would have been previously siloed – transport, energy, connectivity – the team has been able to begin to test new radical solutions for the city. Although at an early stage, this work will form the basis of the city's 'digital twin' strategy and by proving value at an early stage will help to engage decision makers and funders in scaling the early-stage work into a city-scale project.

Dan Clarke, Digital Programme Manager, Cambridgeshire County Council

Contact: CSIC Research Associate Dr Timea Nochta
CSIC team: Dr Timea Nochta, Dr Li Wan, Dr Junqing Tang, Dr Jennifer Schooling
Smart Cambridge team: Dan Clarke and Gemma Schroeder, Programme Manager, Cambridgeshire County Council

Research projects

CSIC continues to innovate at the cutting edge of research. The following pages showcase a number of current research projects using integrated, data-driven solutions to enable better decision-making to reduce carbon, increase resilience and preserve resources.

The key objectives of CSIC are to advance research in smart infrastructure and create impact in the infrastructure and construction industry. The following research projects – ranging from affordable robotics to support material efficiency in the construction of concrete buildings and systems integration to support more resilient infrastructure, to an augmented reality inspection system for the operations and maintenance of built assets – demonstrate CSIC's wide-ranging and cross-disciplinary approaches to smart infrastructure solutions.

Research project 1
Affordable robotics to support material efficiency, productivity and sustainability in construction of concrete buildings

Research project 2
Developing new analyses to estimate seabed cable fatigue life

Research project 3
Systems integration for resilient infrastructure

Research project 4
Visualised inspection system for monitoring environmental anomalies in operation and maintenance management

Affordable robotics to support material efficiency, productivity and sustainability in construction of concrete buildings

The widespread use of flat panel formwork for concrete leads to materially inefficient prismatic shapes for the beams, columns, and floor-slabs in our buildings. This practice, which has been around since Roman times, is both architecturally constraining and a key driver behind the high embodied carbon emissions associated with concrete structures. As a liquid, concrete can form structures of any shape, given the correct mould, and can be produced off-site in a highly automated, quality-controlled environment. By using robotics to create an optimised shape, buildings could become more aesthetic and resource efficient and the construction industry more productive.

A robotic arm has been placed on to the strong floor at the National Facility for Infrastructure Sensing (NRFIS), in the new Civil Engineering Building (see page 22), as part of the Automating Concrete Construction (ACORN) project, a collaboration between researchers at CSIC and the Universities of Bath and Dundee, and multiple partners from across the construction and built environment industry. The ACORN team will create an end-to-end digital process to automate the off-site fabrication of non-prismatic building elements, capitalising on the recent proliferation of affordable robotics and bring them into an industry ripe for a step-change in sustainability and productivity.

Linking robotic manufacture to design

ACORN's focus on automated manufacturing and digital processes to reduce both fabrication and build time are key ways of realising better value. By moving the manufacture of structural concrete elements into a highly controlled factory environment, the project will ensure that buildings can become more sustainable and the construction industry more productive.

Using a robotic arm, programmed to apply concrete only where necessary, the team intend to demonstrate that material efficiency will enhance sustainability and productivity. Taking this approach at the design phase of any construction project brings potential for enormous savings. The project is at the early stage and embedded sensors monitoring performance both in the lab and on-site will feature as the prototype project develops.

The team are considering the long-term benefits of this process as well. Once the structure is in place, sensors will be returning information to inform the next stages, monitoring the structural health and performance of the building throughout the lifetime of these structures.

This manufacturing process, including formwork, reinforcement placement and sensor integration, would see added benefits; workers would increase their skills, safety would be improved, and manufacturing costs reduced.

Resource efficiency

Construction accounts for nearly half of the UK's carbon emissions, and cement manufacture alone for five per cent of global CO_2 emissions. By moving the construction of concrete buildings off-site, to a highly automated, quality-controlled environment, and using robotics to create optimised non-prismatic formwork, our buildings can become resource efficient and the construction industry less polluting and more productive. Designing and building lightweight vaulted slabs with minimised reinforcement, instead of highly-reinforced thick plates – thanks to breaking the constraint of easy-to-fabricate forms – changes how we will construct our buildings of the future. A prototype building on the BRE (Building Research Establishment) Innovation Park at Watford will act as a demonstrator of the research and developments at the end of the project in late 2021.

Contact: Research Associate Dr Robin Oval
CSIC team: Dr Robin Oval, Dr John Orr
Industry team: Neil Abbott, Director of Construction, BRE, Francis Aish, Head of Applied Research Foster + Partners

Developing new analyses to estimate seabed cable fatigue life

The UK offshore wind sector is a global leader and integral to generating clean electricity helping to decarbonise the economy and contributing to global efforts to tackle climate change. Cable stability, and its impact on fatigue life of the cables, is of increasing concern for the resilience of wind farm energy production in the UK. In this project, CSIC is carrying out experimental validation of models for fatigue life of the cables and developing new instrumentation to provide better estimations of fatigue damage and residual life of cables used in offshore wind farms (see Figure 1).

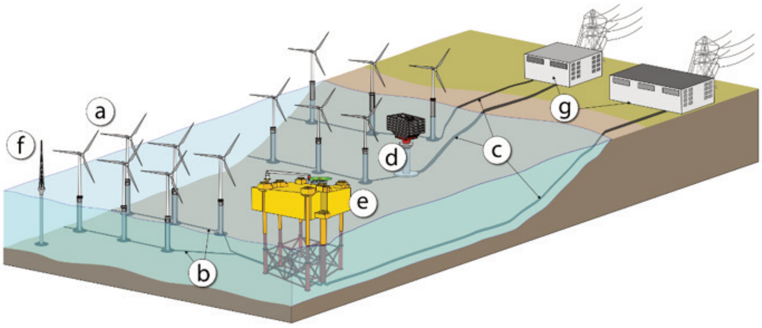


Figure 1: Main components of an offshore wind farm: (a) Wind turbines; (b) Collection cables; (c) Export cables; (d) Transformer station; (e) Converter station; (f) Meteorological mast; (g) Onshore stations (after Rodrigues et al. 2016)

The importance of better estimation of fatigue life for offshore cables

Offshore cables are usually laid in a trench, but where they connect to other elements of the wind farm infrastructure, they must emerge from the trench to the connection point. As they emerge from the trench, they are exposed to buffeting by the ocean currents, which can cause movement and ultimately fatigue and failure. Cable replacement is costly, as is the impact of cable failure on operations. Therefore, accurate fatigue life estimation can reduce cost through avoidance of early replacement, while avoiding the disruption and cost of failure.

Modelling fatigue life

In order for the cable to move, the force on it must be sufficient to move both the cable and the sediments it is emerging from. This is called the 'horizontal breakout force', H. Current numerical modelling techniques often assume the cable is restrained on the seabed by simple friction, often with a coefficient of friction, μ, of 0.5. This simple approach implicitly ignores the beneficial effect of any partial embedment on cable stability when such a model is incorporated into finite element analyses (FEA) in order to predict fatigue life.

Alternative cable-seabed interaction models calculate H by taking account of partial embedment. In Figure 2, the black dotted line shows the model for H if μ is constant at 0.5, and if the surrounding sediments are having no effect in restraining the cable. In fact, as the cable embedment increases, the breakout force will increase significantly. The curved lines show various alternative models for this, developed both a-priori and from some limited experimental observations. At low vertical force per unit length (the conditions most relevant as fluid flows laterally past the cable generating lift and reducing the effective weight of the cable) these can give estimates of H that increase by a factor of 50-100. Utilising simple friction erroneously in FEA analysis can result in overly conservative estimates of fatigue life, resulting in early replacement of cables and high maintenance costs. However, it is not clear which of the alternative models is most appropriate, hence, it is important that we assess this through rigorous experimental verification, both in the laboratory and in the field, if possible.

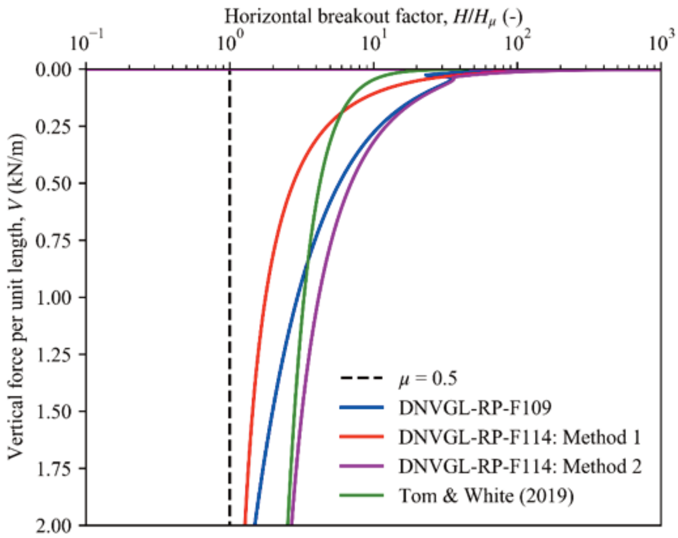


Figure 2: Various models of horizontal breakout factor for a partially buried cable (embedded to half the cable diameter) including: DNVGL-RP-F109, DNVGL-RP-F114 and Tom & White (2019)

Current work and next steps

CSIC research in this area is focussing on:

(i) experimental validation of cable breakout models, such as that proposed by Tom & White (2019), using small scale models
(ii) assessing the impact of incorporating such models into the FEA of cable stability in collaboration
(iii) development of a prototype fatigue damage warning system using fibre-optic technology.

References:

Rodrigues, S., Restrepo, C., Katsouris, G., Pinto, R.T., Soleimanzadeh, M., Bosman, P. and Bauer, P. (2016). A multi-objective optimization framework for offshore wind farm layouts and electric infrastructures. Energies 2016, (9), 216: 1-42. doi:10.3390/en9030216.

Tom, J. G. & White, D. J. (2019). Drained bearing capacity of shallowly embedded pipelines. Journal of Geotechnical and Geoenvironmental Engineering, 145(11). Ahead of print. doi: 10.1061/(ASCE)GT.1943-5606.0002151

Det Norske Veritas (2007). DNVGL-RP-F109: On-bottom stability design of submarine pipelines. Available online.

Det Norske Veritas (2017). DNVGL-RP-F114: Pipe-soil interaction for subsea pipelines. Available online.

Contact: CSIC Investigator Dr Sam Stanier
CSIC team: Dr Sam Stanier, Professor Giulia Viggiani, Maria Chalakatevaki
Industry team: Dr Andrew Lennon, Cura Analytical

Systems integration for resilient infrastructure

The M6 motorway bridge that crosses the Penk River in Staffordshire and (inset) diagonal cracking and moisture accumulation in the deteriorating half-joint connection of the bridge

CSIC is working with industry partner Highways England and Kier Group to identify emerging sensing technologies and approaches for the structural assessment and deterioration detection of static highways assets. CSIC has been tasked with exploring the capabilities of acoustic emission (AE) sensing technology for the structural health monitoring of concrete bridges.

The structural condition of motorway bridges is commonly monitored through periodic site inspections, which result in significant cost and traffic disruptions that may be hazardous to road users. Even if these inspections are enhanced by conventional crack monitoring or surveying methods, the underlying deterioration in critical structural members is hard to assess.

A systems integration approach that brings together multi-sensing systems, ICT, computer vision technologies, cloud data management, statistics and big data analytics may offer a better understanding of underlying deterioration and overall structural performance, enabling effective structural alert systems for asset management.

High-end multi sensing systems

Acoustic emission sensors

AE sensing is a non-destructive testing (NDT) method. Unlike ultrasonic testing, AE is a passive technique that does not require external triggering, which makes it suitable for continuous remote monitoring of civil infrastructure. Well established in other areas of application, including pipeline networks, composite vessels and pressure equipment, the sensors receive and record energy release originating from leakage, cracking or corrosion, and can alert asset managers to the onset of damage.

While the application of AE technologies to monitor reinforced concrete deterioration in bridges is relatively novel, although it is an established method to detect wire breaking in suspension/cable stay and post-tensioned concrete bridges because wire breaking radiates a high energy acoustic wave resulting in a distinguishable signal.

Securing rich information

While effective, the monitoring of wire breaking in cables and tendons does not reflect the full potential of AE sensors for the study of deterioration in concrete bridges. There is also opportunity to secure rich information about (i) the early detection and 3D mapping of cracks in the body of concrete, and (ii) the mode and severity of the damage and the state of the structure by taking into account the entire information from the waveform of the AE signal. This is facilitated by recent advances in signal processing, clustering data analysis, AI and statistics.

Collaborating for shared benefits

CSIC is partnering with leading asset protection specialists to test, verify and further improve AE sensing systems and processing algorithms through detailed lab testing and alternative high-performance multi-sensing monitoring on site. This three-way collaborative research project is designed to accelerate industry uptake of the resulting innovative monitoring solutions.

The project will use AE sensors to monitor the half-joint – one of the most critical parts of a concrete bridge – which suffers from fatigue and moisture accumulation; a local failure may lead to partial or total bridge collapse making early detection and characterisation crucial. Many studies have been conducted to understand the behaviour of half-joints under monotonic loading, but knowledge of performance on cyclic or fatigue loading is limited.

Designing and developing a multi-sensing system

During two project phases – Develop and Demonstrate – CSIC will design and develop a multi-sensing system, comprising AE sensors, fibre optic strain sensors and environmental sensors in the lab. Detailed strain and environmental monitoring will help to interpret AE signals and verify the results of damage localisation and characterisation algorithms.

CSIC has new optical distributed sensing equipment for high-spatial resolution strain monitoring of concrete specimens. This information, together with strain field measurements from Digital Image Correlation (DIC) will be used to validate AE algorithms for early cracking detection and 3D mapping of damage.

Feature and waveform based AE analysis for source discrimination, source localisation and severity assessment will be tested, together with advanced signal processing algorithms (AI, advanced statistics and pattern recognition). The research project aims to understand the benefits and limitations of each approach and develop an optimum data processing methodology to improve data interpretation for half-joint bridges.

The ultimate goal of this research project is to develop real-time systems to detect the crack, and also identify the location, mode and severity of the damage to contribute significantly to the structural performance assessment of the structure.

Proof of concept monitoring with AE sensors

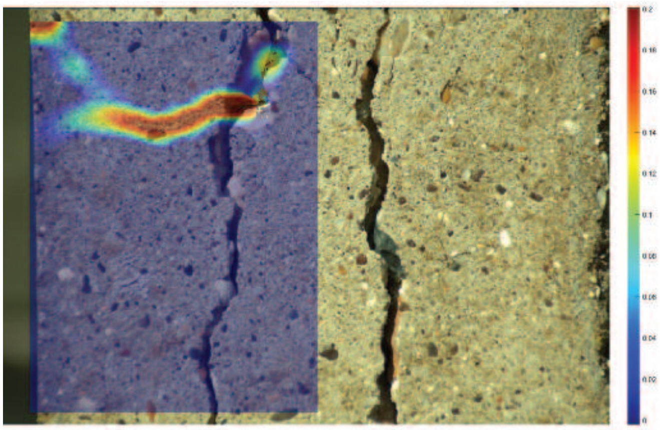
A damaged half-joint on a concrete bridge carrying the M6 motorway over the River Penk in Staffordshire, UK, will be instrumented with 24 AE sensors. A network of 80 fibre Bragg grating (FBG) sensors will be used to correlate the AE-monitored behaviour of concrete with deformation and validate the results from the damage severity and localisation AE algorithms developed during the experimental studies.

Sensors will be installed along the 40m-wide half-joint connection to detect weak regions and underlying deterioration such as reinforcement corrosion and internal cracking. This is critical information that is not accessible through site inspection. At selective locations, damage localisation will be attempted. The accuracy in detection of weak regions and damage will be assessed through correlation with FBG dynamic strain monitoring. Data from FBG temperature sensors and a weather station installed on the bridge will be used to decouple normal seasonal responses from structural deterioration.

Outcomes and benefits

The outcomes and benefits from this research project will: confirm the effectiveness of AE sensors for damage characterisation and localisation in concrete bridges through multi-sensing information and laboratory studies; test existing and develop new sophisticated algorithms for AE monitoring systems; optimise monitoring arrangements for concrete highway bridges; and provide continuous asset condition and degradation monitoring, enabling early warning systems and a 'predict and prevent' maintenance strategy.

Using computer vision to further understand bridge deterioration



An example of measuring crack opening in the vertical direction

Computer vision technologies are currently more versatile and efficient than ever before due to the development of cameras and computation power. Applying computer vision makes possible the deployment of novel solutions, ranging from advanced cameras measuring micron displacement of bridge defects to battery powered Internet-of-Things (IoT) systems tracking elements in a scene such as cars or trains. Digital image correlation is a full field displacement measurement technique with sub-pixel resolution that can map out the deformation. It is a very efficient tool to analyse local defects or crack formation with accurate measurement directly overlaid onto images of a concrete section.

It is also possible to deploy low-cost time-lapse cameras on more remote projects to track the evolution of different phenomena such as water leaks, traffic or changes in environment. The daily visual observation will enhance the data collected by other sensors, including fibre optics, providing better context and support to identify the main cause of damage. Such techniques can make use of commercial cameras that are more accessible and cheaper compared to other scientific instrumentation, which could support future deployments on other Highways England bridges.

Cloud data management and curation of real-time bridge monitoring data

CSIC aims to create a cloud-based data platform for asset management through the creation and integration of numerous digital twins modelling infrastructure networks. Data curation, management, and sharing strategies play a vital role in preparing to meet this long-term vision. Real-time monitoring data from different assets can be analysed and shared through well-defined and agreed protocols to make integrated and sustainable asset management practices possible. Interoperability, systems-of-systems perspective and sustainable decision-making would be the core of this platform. Securely sharing the appropriate information with the different stakeholders enables overall digital twin integration, management and monitoring which would change the future of smart infrastructure management. The findings and rich information that will be collected throughout the Highways England Systems Integration for Resilient Infrastructure project and the proposed cloud-based data platform may contribute towards the National Digital Twin programme.

The Centre for Digital Built Britain's National Digital Twin programme aims to steer the successful development and adoption of the information management framework for the built environment, and to create an ecosystem of connected digital twins – which opens the opportunity to release value for society, the economy, business and the environment. CSIC's collaborative project with Highways England has potential to become one of many digital twins that would benefit stakeholders from effective information management through cloud-based data platforms which will enable interoperability and data sharing between different assets.

Acknowledgements

This project has been supported by the local community near the Penk River Bridge. CSIC is grateful to Jeff Lowe, Technical Director at Technobrake Ltd t/a Doctor Air Brake for providing electric power and space for the fibre optic analyser, and Richard Bower, land owner of Lower Drayton Farm, for providing space and facilitating the deployment.

Contact: CSIC Research Associate Dr Haris Alexakis
CSIC team: Dr Haris Alexakis, Dr Jennifer Schooling, Dr Cedric Kechavarzi, Dr Nikolaos Tziavos, Dr Didem Gürdür Broo, Dr Vladimir Vilde
Industry team: Ian Billington, Consultant Innovation Project Manager, Highways England, Mark Sheppard, Senior Project Manager, Kier Highways

Visualised inspection system for monitoring environmental anomalies in operation and maintenance management

Monitoring building environmental conditions – such as temperature, humidity and CO_2 concentration – is important for effective and effcient operations and maintenance (O&M) of built assets. The workplace environment should contribute to occupant wellbeing and productivity but also reduce operational carbon associated with the provision of thermal comfort. Facility managers need accurate and timely information to detect environmental anomalies and make informed decisions on operation and maintenance. Taking temperature as an example of indoor environmental indicators, this project seeks to address the knowledge gap facility managers face in automatically detecting and interpreting temperature anomalies of building spaces in O&M phases to facilitate better decision-making.

Smart infrastructure asset management

Current O&M services retain a high degree of visual inspection and judgement-based decisions, especially with hidden assets such as plumbing. An intelligent system that assists asset managers' visual inspection to simultaneously record, communicate and verify O&M issues is required.

Research suggests that automated and digital data capture and management systems utilising Building Information Modelling (BIM) can significantly reduce the time taken to update databases used in O&M phases. BIM can be used as an information source and a repository for supporting various activities in existing buildings, but requires integration of digital twin (DT) concepts (a dynamic twin with input of current performance data from the physical asset via live data flows and feedback into the physical twin via real time control[1]) for whole-life cycle asset management in the O&M phase.

Design and methodology

In order to develop an intelligent, easy-to-use and practical visualised inspection system for daily O&M management, CSIC researchers developed an inspection system based on building DTs, specifically focused on spatial temperature anomalies.

The proposed augmented reality (AR) inspection system deeply embodies the daily O&M management process (Figure 1). Various O&M data resources are integrated through the building DT platform. Supported by computational power provided by the DT, anomaly detection functions are designed to identify asset-related anomaly issues, and a query builder module is used which extracts data from the multiple data sources accordingly. Also, the required O&M knowledge, built using fault trees – a tool to help identify potential causes of system failures before the failures actually occur – and matching strategies, is stored using knowledge representation methods. A decision-making tree is also created, aiming to implement matches between detected anomalies with corresponding failed assets to further support decision-making. Additionally, a visualisation enhanced inspection tool (using AR equipment) is launched, highlighting assets that may have contributed to the anomaly – particularly for hidden assets – with their related information. Following O&M processes, assigned site workers can also find the target asset using the AR equipment.

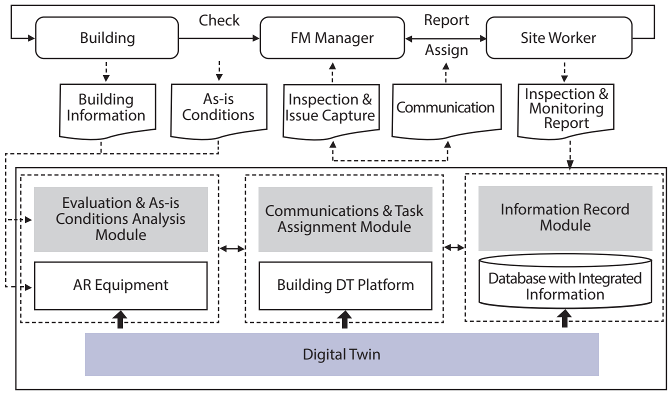


Figure 1: The proposed process of the visualised inspection system in daily O&M management

West Cambridge Digital Twin Pilot

The proposed inspection system has been implemented as part of the Centre for Digital Built Britain (CDBB) West Cambridge Digital Twin Pilot, and will ultimately provide intelligent and visualised inspection environment for facility management. DT with BIM embedded plays a significant role in facilitating the availability and accessibility of heterogeneous environmental parameters. This enables data from different stakeholders in the O&M phase of a building to be created, shared, exchanged and managed. Data-centric analytical tools are widely used in this process, automatically extracting anomalous environmental behaviours that do not conform to anticipated behaviours. This system enables inspection to be quantitatively executed and as-is conditions to be automatically recorded, conveniently verified and intelligently analysed.

Benefits and value

The proposed system has the potential to help site workers and facilities management (FM) professionals to understand better the nature (types and extents) of different hidden assets in a visualised format. The system would provide a smarter way to schedule effective interventions and plan for timely inspection in the future.

The development of a visualised inspection system for O&M management has great potential towards enabling a sector where collaborative work can be further improved via an intelligent, extensive, interoperable, sharable and geometric visual platform. This AR-supported visual inspection system also provides the possibility of establishing DT-based smart management which will both monitor the environment or asset in real-time and have predictive capabilities.

Contact: CSIC Investigator Dr Ajith Parlikad
Team: Dr Ajith Parlikad, Dr Quichen Lu, Dr Xiang Xie

[1] The Gemini Principles, Centre for Digital Built Britain and Digital Framework Task Group (2018)

Data as a journey, not a destination

Dr Didem Gürdür Broo, CSIC Research Associate

High-quality, trustworthy data can help organisations build strategies, capture value, increase the potential of automation and enable insightful and fast decision-making. Data could change the places we inhabit through enabling real-time solutions to challenges such as traffic congestion, air quality, energy distribution and monitoring. Only the collection, curation and whole-life accessibility of high-quality data can help us to optimise the performance and maintenance of our existing infrastructure, including roads, railways, bridges, buildings and undergrounds. This could make a big difference in a country where we add 0.5 per cent annually to the capital values of our inherited assets[1].

> "Only the collection, curation and whole-life accessibility of high-quality data can help us to optimise the performance and maintenance of our existing infrastructure, including roads, railways, bridges, buildings and undergrounds … reliable data enables us to use our infrastructure efficiently, bringing a sustainable, carbon-free world within reach.

The availability of accurate, reliable data enables us to use our infrastructure efficiently, bringing a sustainable, carbon-free world within reach. However, despite this potential, research shows that as few as 10 per cent of companies are attempting to put data and artificial intelligence to work across their businesses. Some industries such as telecommunications, automotive and financial services are doing relatively well catching up with the level of maturity seen in information and communication technologies. Others such as health care, education, government, and construction are still not close to realising the full potential of data.

Adopting data-oriented approaches is a destination, yet that point cannot be reached without taking the journey. This journey requires organisations to curate, collect, assess, analyse, algorithimise, visualise and operationalise data. The process can be long, and new skill sets and perspectives are necessary – as well as investment – for a successful application. The opportunities are limitless and the change is inevitable.

Data can be referred to as "the new oil". This metaphor is at once exciting and scary. Today we are, on one hand, grateful for the changes that oil fuelled. Yet, one of the world's biggest struggles today is waste from this revolution. Now that we are at the beginning of a new era, which many call the fourth industrial revolution, it is vital to understand how data-related decisions of today can affect the future and minimise waste from the start. It is essential to acquire the fundamentals of data, know how data will be useful for our industry and learn the lessons of other industries to avoid repeating their mistakes.

To this end, our strategy should be not only collecting data but collecting the right amount of data for the right purpose, instead of collecting data without a well-defined objective. This requires orgaisations to ask important questions, put initial data management plans into action and continuously check the quality of the data. To enable sustainable, optimised decisions we need not only data but also data from others making discussions on how to integrate and share data more important than ever. If organisations want to be able to compete, profit and help to build a sustainable world, the decision-makers must start embracing data, hire the right people and put in place necessary policies to gather the correct data, make data accessible and assess the quality. Only in this way will our industry be in a position to truly take advantage of the next industrial revolution.

[1] Smart Infrastructure: Getting more from strategic assets, CSIC and industry partners, June 2017

Impact and outreach

Raising awareness of the Centre's research is a key part of CSIC's ambition to transform infrastructure and construction. Every year our programme of events is designed to share our research and policy outputs with infrastructure and construction partners and colleagues, supporting them in finding solutions to real industry challenges. As well as hosting lectures, bespoke training sessions and workshops, members of the CSIC team also contribute to roundtables, panels, conferences and industry events. CSIC research has attracted many awards and industry commendations.

CSIC events

The International Conference on Smart Infrastructure and Construction (ICSIC)

ICSIC 2019 was held at Churchill College Cambridge and brought together world-leading experts from the increasingly dynamic field of smart infrastructure and construction including academics, practitioners and policy-makers from infrastructure planning, construction, asset management, smart cities and sensing. The three-day conference, held in July, was attended by 200 delegates and included more than 80 presentations, several lunchtime workshops, a conference exhibition and poster area displaying some of the latest innovations in smart infrastructure and construction.

Many of the presentations across smart sensors, structures, geotechnics, asset management, policy, digital, data analytics and cities are now available to view on the ICSIC YouTube channel. Keynote presentations by Dr Keith Bowers of COWI, Professor Jerome Lynch of the University of Michigan and Professor Yozo Fujino of the Institute of Advanced Sciences, Yokohama National University, as well as our best paper presentations can also be viewed. The online papers are available from the Institute of Civil Engineers (ICE) Virtual Library. Printed proceedings can also be purchased directly from CSIC. "Our industry is embracing the digital revolution and this was clearly shown by the innovations being presented at ICSIC 2019. We hope the conference has played a part in sharing ideas and knowledge that will advance smart infrastructure and construction," said Dr Jennifer Schooling, Director of CSIC.

Achieving Net Zero Roundtable

CSIC hosted a cross-government and industry roundtable discussion on Achieving Net Zero in March 2020. The event, which was organised by CSIC, Arcadis and COWI, invited a range of representatives from government, policy and the infrastructure and construction industry to consider: what design and site measures can be adopted to reduce waste and move towards achieving net zero; how can existing data and digital tools be exploited to achieve this target; given the climate emergency and government commitment to net zero by 2050, what changes to their procurement documents and processes can public sector, regulated industry and private sector clients make immediately, and what further actions can government ask of asset owners and project clients under existing powers? The group continues to meet with the objective of actively moving the Net Zero Carbon agenda forward in our industry. The group has established some key priorities and is pursuing actions towards achieving these.

Service Oriented, Holonic and Multi-agent Manufacturing Systems for Industry of the Future (SOHOMA)

CSIC Investigator Professor Duncan McFarlane was a key speaker at the ninth annual SOHOMA event, held in Valencia, Spain in 2019. The main focus of the SOHOMA event is to foster innovation in smart and sustainable manufacturing and logistics systems. This year's theme was 'Smart anything everywhere – the vertical and horizontal manufacturing integration' and the two-day programme featured a number of workshops including 'From BIM towards Digital Twin: Strategy and Future Development for Smart Asset Management' led by CSIC Investigator Dr Ajith Parlikad, CSIC Director Dr Jennifer Schooling and CSIC Researchers James Heaton, Qiuchen Lu, and Xiang Xie .

CSIC Digital Cities for Change seminar series

Funded by the Ove Arup Foundation and the Centre for Digital Built Britain (CDBB), DC2 evaluates both existing structures and systems of city and infrastructure management investigating how digital tools can inform better decision-making. DC2 hosted its first in an ongoing series of multidisciplinary seminars in March 2019, which feature a range of speakers and invite debate and discussion. Each seminar is presented on a different theme and past seminars have explored subjects including: smart cities and the interaction with society; governance of the smart mobility transition; urban technologies for refugee integration; and understanding adaptation planning of urban road infrastructure. Details of the DC2 seminar series can be found on the CSIC website.

CSIC Partner Summer Party and official opening of new Civil Engineering Building

CSIC hosted its annual partner party at its new home in the Civil Engineering Building on the West Cambridge Campus; the building was officially opened by Andrew Wyllie CBE, former President of the

Attendees at the International Conference for Smart Infrastructure and Construction (ICSIC) 2019

Colleagues at the CSIC Summer Party

Attendees at the CSIC Partner Strategy Day

Award winner Melanie Jans-Singh and event organisers

Institution of Engineers on the same day. The party, which was attended by many representatives from CSIC partner organisations including Highways England, HS2, TfL, Mott MacDonald and Bentley Systems, featured a number of fast-paced presentations showcasing a range of CSIC projects from research assistants and students, while fizz and canapés were served.

The event was also an opportunity for partners to tour the new Civil Engineering Building, which houses the National Research Facility for Infrastructure Sensing (NRFIS) and has 12 world-class, state-of-the-art laboratories, including CSIC's new Smart Infrastructure and Construction lab, focusing on a variety of civil engineering disciplines, including sensor development, structures, geomechanics and construction.

CSIC Partner Strategy Day

The annual CSIC Strategy Day held in November 2019 brought together partners, academics, and policy-makers to identify and discuss pressing industry challenges that CSIC's future research agenda will seek to address. Robinson College hosted the fully-booked event, which attracted 30 partners from across infrastructure and construction organisations and focused on issues relating to global challenges, climate change, resilience and resource scarcity. A paper capturing key points from discussions was distributed to attending partner organisations.

External impact

Awards

New Civil Engineer TechFest Rail Visionary awards

CSIC's innovative system of monitoring the health of ageing railway infrastructure won the New Civil Engineer TechFest Rail Visionary Award. The University of Cambridge, Innovative Structural Health Monitoring of Ageing Railway Infrastructure and Smart Monitoring for Condition Assessment of Ageing Infrastructure (a collaboration between CSIC, AECOM, Network Rail and The Alan Turing Institute) showcases two bespoke monitoring systems designed for a skewed masonry arch bridge and masonry arch viaduct, both in Yorkshire. As well as enabling fundamental research into the behaviour of these heritage structures, the detailed monitoring data is also being used to research novel, statistical-based approaches to asset management and structural assessment, through collaboration between CSIC and the Turing. Furthermore, on the skewed bridge project, Network Rail wanted to explore monitoring technologies which have the potential to be used on other assets.

New Civil Engineer (NCE) Tunnelling Festival awards

A CSIC monitoring and modelling system optimising energy-efficient growing conditions at an underground hydroponic farming facility housed in former WW2 air raid shelters 33 metres below the busy streets of Clapham, London won the Innovation in Tunnel Fit-Out, Operations and Maintenance Award at the New Civil Engineer Tunnelling Festival Awards 2019. CSIC Investigator Dr Ruchi Choudhary, who leads the Energy Efficient Cities initiative (EECi) at the Department of Engineering, and her team, including PhD students Melanie Jans-Singh (pictured receiving the award above) and Rebecca Ward, have been monitoring and modelling the tunnels for three years. Results to date have enabled modification of ventilation configurations, lighting schedules, and location of crops, yielding 25 per cent increase in crop yield.

ICE President's Medal

Dr Jennifer Schooling OBE was awarded the President's Medal by Andrew Wyllie CBE, former President of the Institution of Civil Engineers (ICE). The President's Medal is awarded annually by the ICE president to an outstanding civil engineer. The citation for the President's Medal defines CSIC as "operating at the very leading-edge of our new industry, helping to create a wealth of new opportunities for civil engineers around the world to fulfil our purpose of improving lives in our global society". CSIC Investigator Dr Giovanna Biscontin and former University of Cambridge researcher Dr Yingyan Jin collected the Telford Premium award on the same day in recognition of best papers presented to the Institution. The winning paper 'A Bayesian definition of 'most probable' parameters' was published in Geotechnical Research: Volume 5, Issue 3, September 2018, pp. 130-142.

Best Paper at IWRN13

CSIC Investigator Dr James Talbot and University of Cambridge PhD student Tobias Carrigan won the Best Paper Presentation award at IWRN13, the international railway conference in Ghent, Belgium. The paper titled 'Extracting information from axle-box accelerometers: on the derivation of rail roughness spectra in the presence of wheel roughness' features the CSIC project monitoring vibration of trams in the West Midlands. Dr Talbot and Tobias won an award on the same subject at this year's ICSIC in a paper jointly written with CSIC Computer Associate Paul Fidler.

Impact and outreach

CSIC papers

Flourishing Systems

CSIC and the Centre for Digital Built Britain (CDBB) published a white paper, 'Flourishing Systems: re-envisioning infrastructure as a platform for human flourishing', calling for a fundamental change in how we view and run our nation's infrastructure in the face of climate change and the socio-economic recovery from Covid-19.

The paper's central ideas are simple and radical: that the purpose of infrastructure is human flourishing, therefore infrastructure should be viewed and managed as a system of systems that serves people and the environment. Flourishing Systems is supported by the Department for Business, Energy and Industrial Strategy, the Institution of Civil Engineers, the Institution of Engineering and Technology and the Institution of Mechanical Engineers. Its development was supported by more than 30 key experts and influencers from industry, government and academia. Reaching net-zero carbon by 2050, enabling the circular economy and investing in infrastructure to level up prosperity and wellbeing across the country are systemic challenges that require immediate and collaborative action.

Smart Sustainability

The Smart Sustainability paper is a product of the roundtable discussion hosted by CSIC during the 2018 Global Engineering Conference at the Institution of Civil Engineers in London to explore exploiting data as an engineering tool to mitigate climate change.

The paper focuses on the role and responsibility of engineers and makes the case for exploiting data. It concludes with a call to action for every engineer to make a difference and to "speak up, use data and act now." The CSIC paper Smart Infrastructure: getting more from strategic assets (2017) was the first in this series of CSIC papers.

Industry journals and articles

The Conversation

CSIC Research Associate, Didem Gürdür Broo, has written an article published by The Conversation (theconversation.com) highlighting how, in a changing world, it is the larger tech companies making the most of opportunities that Big Data and AI can provide (14 January 2020). Outlining the challenges to other sectors, including a lack of high-quality data, an established strategy and expertise, she describes data as "the foundation of artificial intelligence." Read Didem's thought piece 'Data as a journey, not a destination' in this Annual Review on page 33.

Civil Engineering Surveyor

Members of CSIC have contributed a number of articles to Civil Engineering Surveyor, the monthly journal of the Chartered Institution of Civil Engineering Surveyors, including:

'Smart Sustainability: the role of engineers and the potential of data to mitigate climate change' by Dr Jennifer Schooling, Director of CSIC (February 2020)

'Intelligent Infrastructure: Bringing smarter innovation to a heritage asset' by Sam Cocking, CSIC PhD Researcher (February 2020)

'Automating concrete construction: digital processes for whole-life sustainability and productivity' by Dr John Orr, Lecturer in Concrete Structures and CSIC Investigator and Dr Paul Shepherd, Senior Lecturer, Department of Architecture and Civil Engineering, University of Bath (March 2020)

'Game changer: simulating wildfire evacuations of small communities at regional scale in California' by Dr Bingyu Zhao, former CSIC PhD Researcher (March 2020)

'A GIS-based infrastructure management system to increase resilience of terrestrial transportation networks' by Dr Ajith Parlikad, Reader in Asset Management at the Institute for Manufacturing and CSIC Investigator and Dr Georgios Hadjidemetriou, CSIC Research Associate.

BIM Today

Sam Cocking, CSIC PhD researcher, wrote about the CSIC smart structural health monitoring of a 150-year-old masonry arch bridge in collaboration with AECOM and Network Rail for BIM Today (September 2019).

Geospatial Engineering 2019

CSIC's award-winning collaborative project designing an early warning solution for slope failures at a mainline railway cutting was featured in the Chartered Institution of Civil Engineering Surveyors Geospatial Engineering 2019-2020.

The article 'On track: Fibre optic sensing for safer real-time rockfall monitoring of rail cuttings' describes the project between CSIC, Network Rail and BAM Nuttall to devise a solution to the problem of landslide monitoring at Hooley Cutting, 25km south of London, which carries the main railway line from London to Brighton through the North Downs.

Modus, Royal Institution for Chartered Surveyors (RICS) magazine

Dr Jennifer Schooling, Director of CSIC, was featured in the July 2019 issue titled 'The Precision Issue' which focused on how data is the currency of the surveyor. Dr Schooling said: "Everyone needs to understand that data about an asset, throughout design, construction and ongoing operation, is as important as the asset itself."

Infrastructure Intelligence

An article written by Dr Anne Kemp OBE, based upon her CSIC Distinguished Lecture, was published in Infrastructure Intelligence (21 June 2019). The article titled 'Engaging our conscience to explore the future' draws attention to the potential of smarter infrastructure to support a healthier and more prosperous society but raises questions about the ethics required to safeguard data use and how to ensure that, as humans, we remain an essential part of the decision-making process.

Dr Anne Kemp OBE

Image: Prism Architectural Ltd








Our people

Leadership

Professor Lord Robert Mair CBE
Head of CSIC
Dr Jennifer Schooling OBE
Director of CSIC

International Advisory Group

Professor Michael Batty CBE
University College London
Professor Yozo Fujino
Yokohama National University, Japan
Professor Jerome P. Lynch
University of Michigan, USA
Dr W. Allen Marr
Founder and CEO of Geocomp
Professor Thomas O'Rourke (Chair)
Cornell University, USA
Professor Bill Spencer
University of California, Berkeley, USA
Professor Hehua Zhu
Tongji University, China

Steering Group

Simon Abbot
Network Rail
Karen Alford
Environment Agency
Dr Keith Bowers
COWI
Professor John Burland CBE (Chair)
Imperial College London
Volker Buscher
Arup
Robert Dean
HS1
Tim Embley
Costain
Mark Enzer
Mott MacDonald
Tom Foulkes
Independent Consultant
Steve Hornsby
Independent Consultant
Adam Locke
Laing O'Rourke
Professor Andrew McNaughton
HS2
John Pelton
Jacobs
Richard Ploszek
Infrastructure and Projects Authority
David Pocock
Jacobs
Stephen Pottle
WSP
Phil Proctor
Highways England
Michael Spencer
IMIA
Dr Scott Steedman CBE
British Standards Institution (BSI)
John St Leger
HS2

Investigators

Dr Christelle Abadie
Lecturer in Civil Engineering
Dr Giovanna Biscontin
Lecturer in Geotechnical Engineering
Dr Ioannis Brilakis
Laing O'Rourke Centre Reader in Construction Engineering
Dr Ruchi Choudhary
Reader in Architectural Engineering
Data-Centric Engineering Group Leader at The Alan Turing Institute
Professor Daping Chu
Head of Photonics and Sensors Group
Professor Roberto Cipolla
Professor of Information Engineering
Dr Mohammed Elshafie
Laing O'Rourke Senior Lecturer in Construction Engineering
Professor Mark Girolami
Sir Kirby Laing Professor of Civil Engineering
Programme Director for Data-Centric Engineering at The Alan Turing Institute
Dr Ying Jin
Reader in City Planning, Urban Design and Modelling
Dr Dongfang Liang
Lecturer in Civil Engineering Fluid Mechanics
Professor Duncan McFarlane
Professor in Industrial Information Engineering
Professor Campbell Middleton
Laing O'Rourke Professor of Construction Engineering
Dr John Orr
Lecturer in Concrete Structures
Dr Ajith Parlikad
Reader in Asset Management
Professor Ashwin Seshia
Professor of Microsystems Technology
Dr Elisabete Silva
Reader in Spatial Planning
Professor Kenichi Soga
Chancellor's Professor, University of California, Berkeley
Dr Sam Stanier
Senior Lecturer in Civil Engineering
Dr James Talbot
Senior Lecturer in the Performance-based Design of Structures
Professor Giulia Viggiani
Professor of Infrastructure Geotechnics
Dr Li Wan
Lecturer in Chinese Urban Development

Our people

Staff

Core Team

Jemma Andrews
Centre Coordinator
Paul Fidler
Computer Associate
Dee Dee Frawley
Programme Manager
Dr Cedric Kechavarzi
Operations Manager
Peter Knott
Senior Technician
Phil Keenan
Business Development Manager
Sophie Taylor
Communications Manager
Candy Smellie
Communications Coordinator
Lisa Millard
Communications Associate
Tianlei Wu
Finance Manager

Research Associates

Dr Haris Alexakis
Dr Khalid Alhaj-Abdalla
Dr Nicky de Battista
Dr Cedric Kechavarzi
Dr Georgios Hadjidemetriou
Dr Miguel Bravo Haro
Dr Farhad Huseynov
Dr Didem Gürdür Broo
Dr Monika Kreitmair
Dr Quichen Lu
Dr Nikolas Makasis
Dr Timea Nochta
Dr Yi Rui
Dr Manu Sasidharan
Dr Talia da Silva
Dr Junqing Tang
Dr Nikolaos Tziavos
Dr Vladimir Vilde
Dr Xiang Xie
Dr Xiaomin Xu

Research Students

Daniel Brackenbury
Enhau Cao
Tobias Carrigan
Sam Cocking
James Heaton
Toby Hill
Melanie Jans-Singh
Kasun Kariyawasam
André Neto-Bradley
Aisha Sobey
Jason Sun
Lihua Wang
Simon Ye
Mingda Yuan

Research Assistants

Juan Canavera-Herrera

From left: Professor Yozo Fujino, Dr Jennifer Schooling, Dr Keith Bowers, Professor Giulia Viggiani, Professor Jerome Lynch and Dr Matthew DeJong at ICSIC 2019

We would like to thank everyone who has contributed to another successful year at CSIC, our Partners, International Advisory Group, Steering Group, current and former staff. In particular, we would like to thank Steering Group members Karen Alford, John Burland, Tom Foulkes, Steve Hornsby, John Pelton and Mike Spencer for their invaluable input to this review.

Introducing the National Research Facility for Infrastructure Sensing (NRFIS)

From left: Professor Simon Guest, Head of Civil Engineering; Andrew Wyllie CBE, former President of the Institution of Civil Engineers; Professor Lord Robert Mair, Head of CSIC; Professor Richard Prager, Head of the Department of Engineering; and Professor Giulia Viggiani, NRFIS Academic Lead

NRFIS is part of the UK Collaboratorium for Research on Infrastructure & Cities (UKCRIC). This is a portfolio of state-of-the-art research and innovation facilities for industry and academic institutions to facilitate leading edge experimental research and collaboration to improve the performance of existing and future infrastructure. NRFIS is an interdisciplinary centre for civil engineering, infrastructure design, construction, operation and asset management.

NRFIS builds on the track record of the University of Cambridge of delivering innovative sensor advancements through its Centre for Smart Infrastructure and Construction (CSIC), CamBridgeSens research network, and the Centres for Doctoral Training in Sensor Technologies for a Healthy and Sustainable Future (STHSF) and Future Infrastructure and Built Environment: Resilience in a Changing World (FIBE2).

The NRFIS laboratories and workshops, housed within the Civil Engineering Building at the University of Cambridge, are available for use by industry and academic organisations along with the opportunity to collaborate with Civil Engineering staff on infrastructure research. Research groups and specialist centres located within the Civil Engineering Building include: Centre for Smart Infrastructure and Construction, Laing O'Rourke Centre for Construction Engineering and Technology, Construction Engineering Group, Geotechnical and Environmental Group, and Structures Group.

General information about the services and facilities available at NRFIS, including the types of laboratories and range of equipment on offer, can be found at www.nrfis.cam.ac.uk.

To explore potential collaborations, book laboratory equipment and find out more about access policy and charges; contact the NRFIS team at enquiries@nrfis.cam.ac.uk.

NRFIS Team

Professor Giulia Viggiani
NRFIS Academic Lead

Dr Pieter Desnerck
Senior Technical Manager

Shelley Arora-Tailby
Senior Project Manager

Contact us

The Cambridge Centre for Smart Infrastructure and Construction
Department of Engineering
University of Cambridge
Civil Engineering Building
JJ Thomson Avenue
Cambridge CB3 0FA

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

CSIC is an Innovation and Knowledge Centre funded by

EPSRC
Engineering and Physical Sciences
Research Council

Innovate UK