UNIVERSITY OF CAMBRIDGE

Transforming infrastructure through smarter information

Annual Review 2019

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

CSIC Partners

Infrastructure clients (owners and operators)

Consultants, contractors and asset managers

Technology and information supply chain

Contents

Foreword

Andrew Wyllie CBE
Chief Executive, Costain Group PLC
President of the Institution of Civil Engineers

> The Centre for Smart Infrastructure and Construction (CSIC) is at the very vanguard of this technological advancement, providing leading-edge collaborative research and helping to support innovative, fast-moving, entrepreneurial organisations deliver a new era of infrastructure service and functionality.

The fourth industrial revolution has well and truly arrived.

Driven by a fusion of rapid technological advancements, every sector of the economy now has available to it an amazing array of new tools and techniques to help deliver exceptional business performance.

Interrelated developments in areas such as artificial intelligence, quantum computing, nanotechnology, robotics and data analytics are providing wonderful opportunities to enhance outcomes and deliver previously unimaginable societal benefits.

The use of robotics is enhancing neurosurgery, the use of data analytics is transforming retail, the use of algorithms is redefining media streaming services. Infrastructure is no different.

Around the world, infrastructure service organisations – old and new – are seizing the opportunities now available to deploy technology to increase the capacity of our infrastructure networks. They are deploying new technology to enhance the customer service provided by our infrastructure, and they are deploying new technology to improve the security of supply and resilience of our infrastructure networks.

To use an engineering analogy, the impact and potential of this fourth industrial revolution on the infrastructure sector is akin to the advent of the railways at a time when canal boats were the norm.

The Centre for Smart Infrastructure and Construction (CSIC) is at the very vanguard of this technological advancement, providing leading-edge collaborative research and helping to support innovative, fast-moving, entrepreneurial organisations deliver a new era of infrastructure service and functionality.

From a Costain perspective, the research we are supporting at CSIC has undoubtedly contributed to our business success, and at the Institution of Civil Engineers (ICE) we are certainly benefiting from the close collaboration with the world-leading expertise and thought leadership emerging from CSIC.

Many congratulations to CSIC on another successful year.

Introduction

Image courtesy of Paul Milsom on behalf of ICE

Professor Lord Robert Mair CBE
Head of CSIC
University of Cambridge

Transforming the future of infrastructure through smarter information is the principal aim of the Cambridge Centre for Smart Infrastructure and Construction (CSIC). Funded by the Engineering and Physical Sciences Research Council (EPSRC), Innovate UK and industry, CSIC's key objectives are to advance research in smart infrastructure and create impact in the infrastructure and construction industry. The development of cutting-edge sensing and data analysis models provides a powerful platform for delivering integrated data-driven solutions to increase the productivity and efficiency of our infrastructure. These enable smarter and proactive decisions, both during construction of new infrastructure and for existing infrastructure. The key underpinning theme of data as an engineering tool is the subject of this annual review, which highlights a range of innovative and timely projects delivered by CSIC.

In his foreword to this review, Andrew Wyllie emphasises the recent rapid technological advancements in increasing the capacity of our infrastructure, enhancing the service to society it provides, and improving its security and resilience. He heralds a new era of infrastructure service and functionality – all underpinned by data as an engineering tool. Jennifer Schooling, in her article (overleaf), focuses on the value of data, how engineers can mitigate climate change, and the necessity of ensuring its proper curation. Karen Alford highlights the importance of data-driven asset management, with emphasis on new technologies such as satellite monitoring, sensors and cutting-edge analytics to provide the data to enhance regular asset inspections.

This review presents a number of case studies demonstrating how CSIC works with its partners to deliver effective solutions for industry, each of these illustrating the importance of data as an engineering tool. One of these case studies describes data-led decision-making to optimise economic growth and development, using a wide variety of data to examine implications of house-building and its location in relation to transport, employment, wellbeing of citizens, and other important societal issues. Two further case studies cover the degradation of roads, including the incidence of potholes, cracks and other types of defects, and the observational method for improving and streamlining the construction of deep excavations. The fourth case study focuses on an innovative fibre optic sensing system for safer real-time rockfall monitoring of railway cuttings, which can be highly susceptible to landslides, with consequent train derailments and lengthy line closures; the real-time data from this system could contribute directly to early warning systems, considerably enhancing rail safely. The final case study charts the development of one of the systems used in the former case study, the FEBUS G1D.

CSIC has now deployed and validated new sensor technologies on more than 100 site demonstrations. Many of these innovations have arisen from a wide variety of active research projects, some of which are described in this review. These include novel energy efficient wireless sensor systems for monitoring fatigue of structures; improving air quality and reducing congestion in cities; fibre optic monitoring of a 150 year old skewed masonry arch bridge; automation of concrete construction; implementation of a GIS-based infrastructure management system to increase resilience of transportation networks; and improving foundation design for wind turbines to support sustainable energy generation in Africa. All of these research projects are leading to the production of novel types of data as an engineering tool.

The University of Cambridge is one of the founding members of UKCRIC (UK Collaboratorium for Research in Infrastructure and Cities) in which CSIC is playing a major role. This review includes an article on the new Civil Engineering Building, to be opened in September 2019, which includes the UKCRIC-funded National Research Facility for Infrastructure Sensing (NRFIS), a state-of-the-art research facility available to academic and industry researchers throughout the UK. The facility will build upon the success of CSIC, focusing on the development and application of advanced sensor technologies for the monitoring of existing and future infrastructure to improve resilience and ensure maximum whole-life value.

These articles, case studies and research projects demonstrate CSIC's continuing commitment to providing leadership in the latest technological developments in infrastructure sensing, data analytics and asset management, all of which are underpinned by data as a key engineering tool.

Data as an engineering tool

Dr Jennifer Schooling OBE
Director of CSIC
University of Cambridge

> We have a responsibility for gaining a clear understanding of the carbon emissions arising from our designs and from our construction activities, with data on materials use, waste and construction processes being critical to quantifying carbon emissions and hence putting in place measures to reduce them.

Through all of our work, CSIC's focus is on 'Transforming the future of infrastructure and construction through smarter information'. Data is at the heart of informed decision-making, with good quality data being the foundation of smarter information.

Improved decision-making

Data is used to provide insights into how our infrastructure is used throughout its life; its condition and capacity to serve those uses; and how we design and construct new assets. It is vital to informing decisions on whether, for a given issue, we should be investing in new infrastructure, or focusing on getting more out of our existing asset base, which forms the vast majority of our infrastructure and represents significant investment by previous generations. Each year in the UK we add just 0.5 per cent to the capital value of our existing infrastructure.[1]

Clearly, the economic value of this vital system must continue to be exploited. Our infrastructure system has been sustained over the last 150 years – however, without due attention being paid to it, it will become increasing unsustainable. This includes gathering data to provide information on the condition and capacity of our built assets, as well as feeding projections for the future demands to be placed upon it, in order to enable better decision-making around maintenance, management and renewal.

Mitigating climate change

Data is also critical as a tool to help us address wider challenges facing our society, and hence our built environment. Perhaps the most critical of these is climate change. CSIC held a roundtable at the 2018 Global Engineering Congress, focusing on the role of data as a tool in mitigating climate change. The discussion included infrastructure engineers and owners, sustainability professionals, and representatives of development banks and the insurance sector. What became clear from the discussion was that engineers have a huge role to play in mitigating climate change. We have a responsibility for gaining a clear understanding of the carbon emissions arising from our designs and from our construction activities, with data on materials use, waste and construction processes being critical to quantifying carbon emissions and hence putting in place measures to reduce them. Such measures include refining designs, based on actual performance data, and reducing cement contents and material wastage. In addition, we have to use information and projections on infrastructure requirements, combined with data on the current and future capacity of our existing assets and systems, to understand where we might avoid building new infrastructure by enhancing the utilisation of existing assets. This avoids embedded emissions and gets the most from our earlier investments in carbon.

Maximising value of data

All of the above relies on us being clear about what data we need to inform which decisions, and then being rigorous in how we collect and manage that data though the life of the infrastructure it relates to. **Data curation is crucial** (see Figure 1). We also need new approaches to how we value that data. Our infrastructure is persistent, lasting for centuries rather than years or decades. We therefore need to consider how we reward good practices that take the 'long view' of data requirements; how we futureproof data throughout the life of the assets it relates to; and how we make that data shareable between relevant stakeholders, as discussed in *Data for the Public Good*[2]. This requires asset owners to recognise the value of data, and the supply chain to collaborate in creating and managing it in an ongoing way.

Our industry is embracing the digital revolution – we now need to transform our operational approaches to enable us to get maximum value from the data we are generating, not just for ourselves but for the generations that follow.

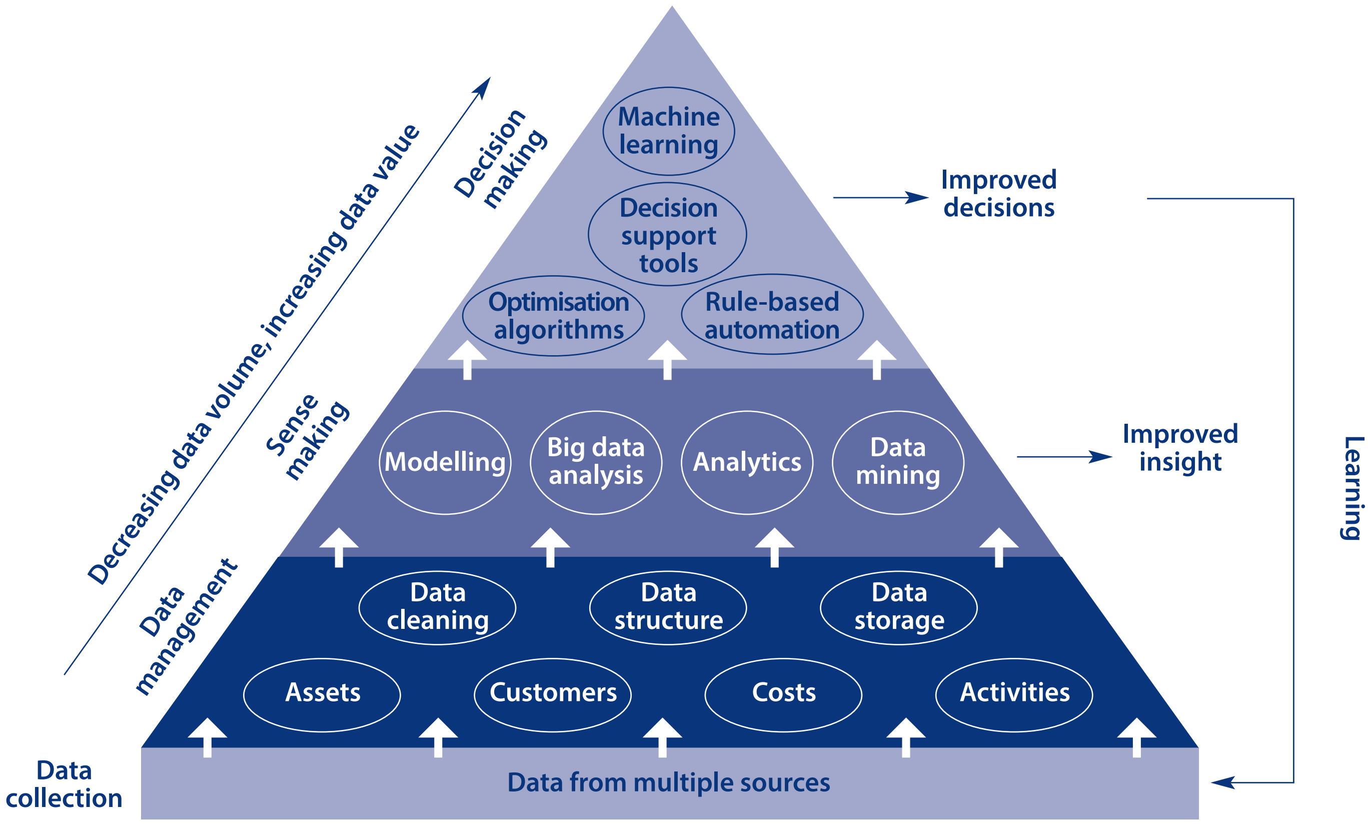


Figure 1: From big data to better decisions[1]
Decreasing data volume, increasing data value. The overlay of this model onto physical infrastructure makes it smart. At the base is raw data and at the apex are decisions – the higher up, the more value the information; the lower down, the greater the volume of data. Information processing occurs within each layer and communication connects both the layers and the outside world.

[1] *Smart Infrastructure: Getting more from strategic assets*, CSIC and industry partners, June 2017
[2] *Data for the Public Good*, National Infrastructure Commission, December 2017

Chesil Beach in Dorset where the Environment Agency completed flood defence work.

Environment Agency

Creating and consuming data: Maximising opportunities of digitalisation for whole-life asset management

Karen Alford
Flood and Coastal Risk Manager for the Environment Agency – Asset Data and Information

Data – originally a Latin noun, meaning 'something given'. Although it first appeared in the 1640s, it wasn't until 1946 that its definition was refined to mean transmissible and storable information – the meaning we recognise today.

The middle of the last century marked a transformation in the range of technology seamlessly shaping our daily lives, from sat navs and smart heating controls, to cars that keep track of their own performance. These technologies draw on data from various sources and apply rules to provide better information and knowledge to those using them.

The advancement of technology brings many benefits. However, I am constantly asking myself these questions: What data is it using? Where does the data come from? What rules are being applied to the data? How are variances being managed and what other technologies are being used to achieve the final outcome?

Just as a physical asset requires good foundations to ensure longevity, the data asset needs to be built on the same strong foundations. Maximising value from the data asset requires better understanding of how data will be used across the operational lifecycle of the asset to inform decisions. Also, we should be mindful that data can have additional application beyond its intended use.

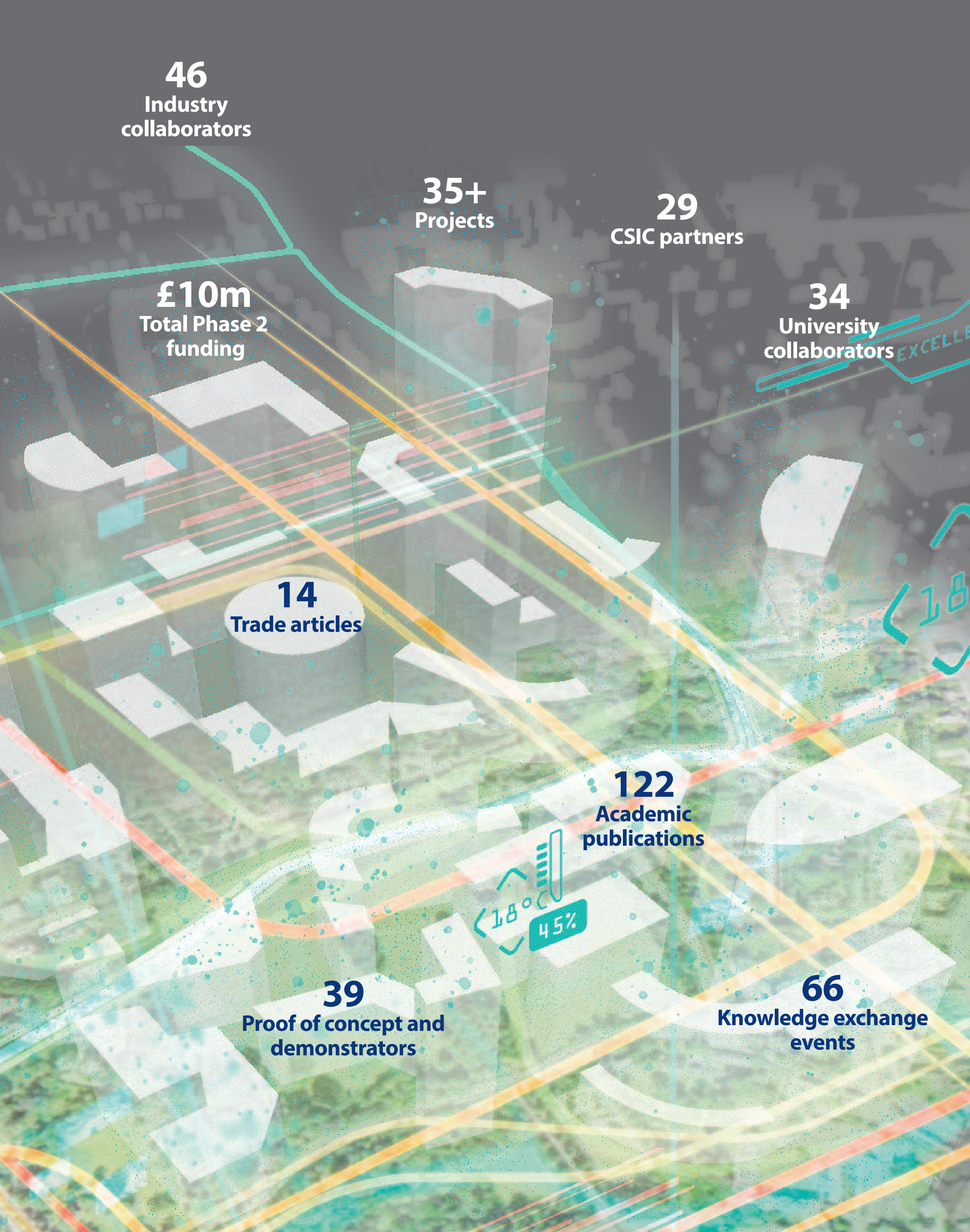
In essence, engineering is the practical application of principles and rules derived from an understanding of physics and mathematics applied to the built environment. This activity has been transformed into a complex set of rules, which when applied to relevant data and information, is turned into knowledge to solve engineering problems. Although construction results in a physical outcome, a lot of data 'giving' takes place across the profession to achieve the goal of whole-life benefit for the asset owner, manager and end user.

Engineers from every discipline within the construction and infrastructure industry are both consumers and creators of data. If the generated data fails to meet agreed standards and rules, it carries a burden to consumers of data or the associated processes which, in turn, directly impacts productivity.

Consumers and creators of data need to adhere to a commonly agreed set of standards and quality parameters and work collaboratively to securely maximise the opportunities of digitalisation and derive the benefits of whole-life infrastructure asset management.

Groundbreaking technological outputs from CSIC research support this data-driven asset management. Of particular interest to me are methods to improve asset condition monitoring that use data to identify issues before failure occurs, including the use of satellite monitoring, sensors and cutting-edge analytics to enhance regular asset inspections. The industry-focused and collaborative work of CSIC is transforming approaches to asset management by providing tools for better decision-making. Using data as an engineering tool in this way brings insight and information to improve and add value to whole-life asset management.

The year in numbers



Work with us

By collaborating with the infrastructure and construction industry and supporting professional organisations and policy makers, CSIC is able to accelerate implementation of research outputs, delivering value by improving margins, reducing costs and extending the productive life of assets. Such collaborations are helping to establish the UK as a global leader in smart infrastructure.

CSIC partnerships

CSIC offers four levels of partnership designed to suit a range of organisations: Full Partners; SME Partners; Micro Partners (less than 10 employees); and Associate Partners, which are typically non-commercial, non-profit making organisations.

Partner organisations operating in the infrastructure and construction sector benefit from engaging with CSIC in a number of ways. Working across seven strategic themes (see below) covering the whole-life of infrastructure, CSIC provides the tools, training and knowledge required to take advantage of the latest technical developments in data analysis and interpretation, asset management and sensor technology. Partnerships enable collaboration, knowledge transfer and open engagement to help industry secure competitive advantage. CSIC innovations and collaborations have attracted industry recognition, resulting in a number of awards and nominations.

Business development and knowledge transfer

CSIC's business development and knowledge transfer team works closely with industry to identify and understand key issues and challenges in order to design, develop and deliver effective and repeatable solutions.

Deployment

The work of CSIC is supported and shaped by our industry partners. Collaboration brings benefits and value to both parties as well as the wider infrastructure community. Testing new tools and technologies at real field sites on live projects accelerates the timeframe for innovations to become part of the construction industry mainstream.

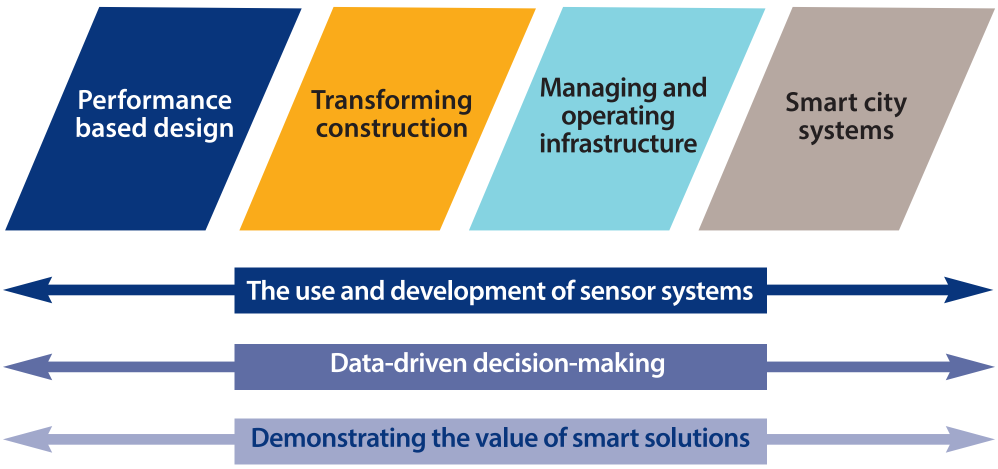
Developing the value chain

CSIC works to develop the value chain by collaborating with key technology suppliers to advance simplified and standardised installation. Working with industry partners supports development of new sensors and monitoring systems that add value to the whole-life performance of our infrastructure and inform better asset management decision-making.

Training and dissemination

Sharing information and knowledge is key to advancing industry adoption of innovative solutions. CSIC is developing a range of routes for disseminating advances in smart infrastructure and construction, including specialist training courses, workshops, best practice guides and case studies.

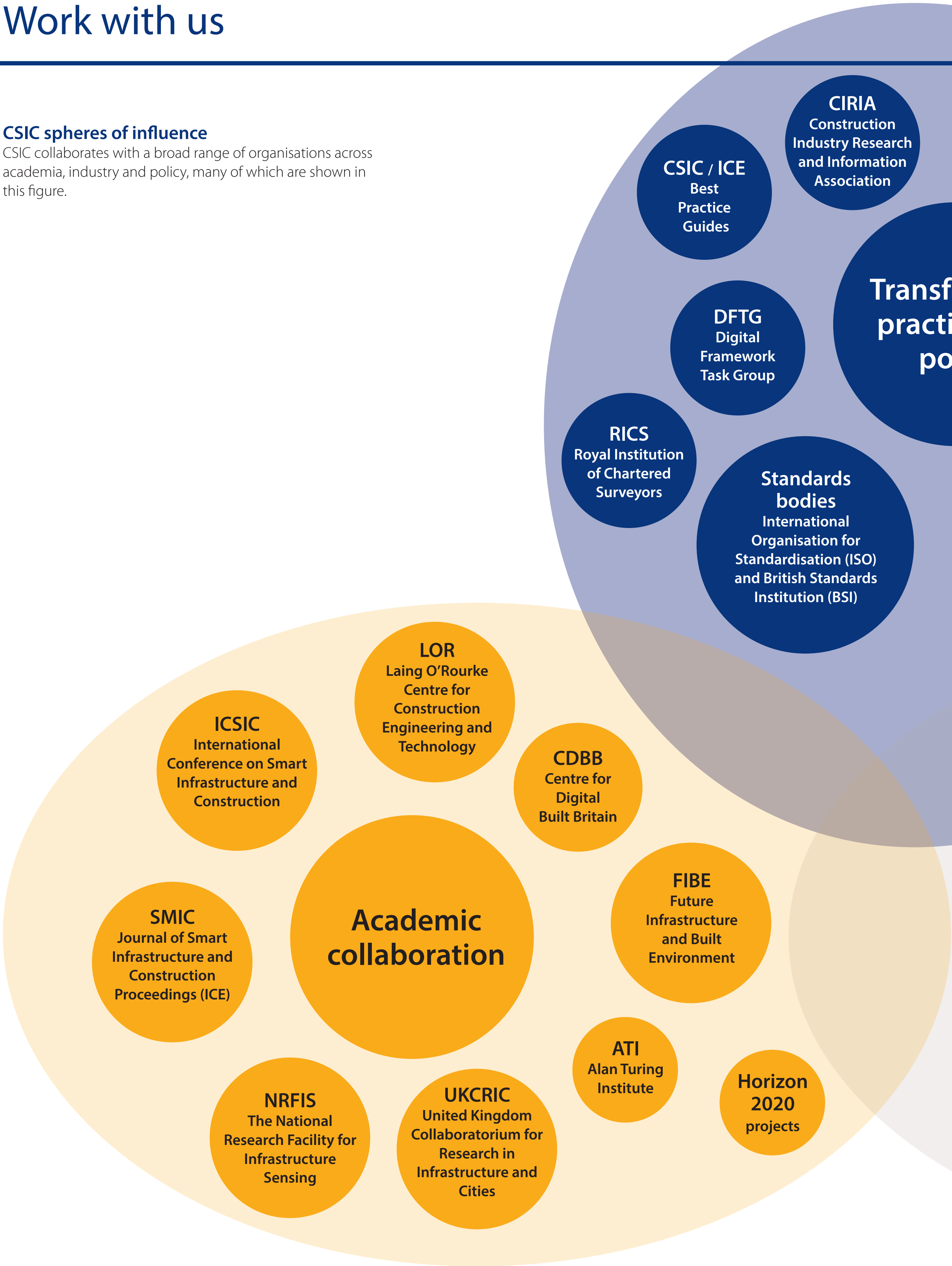
CSIC's strategic themes

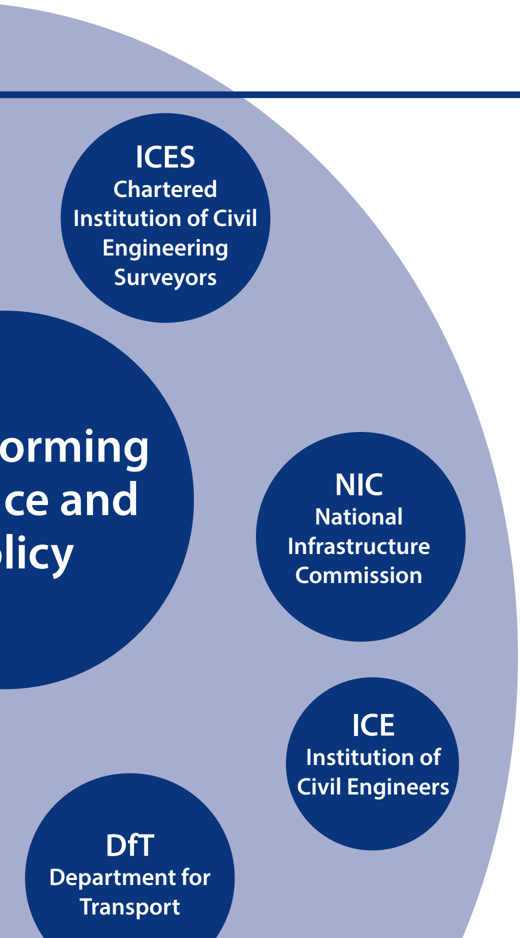


Work with us

CSIC spheres of influence

CSIC collaborates with a broad range of organisations across academia, industry and policy, many of which are shown in this figure.





Get in touch

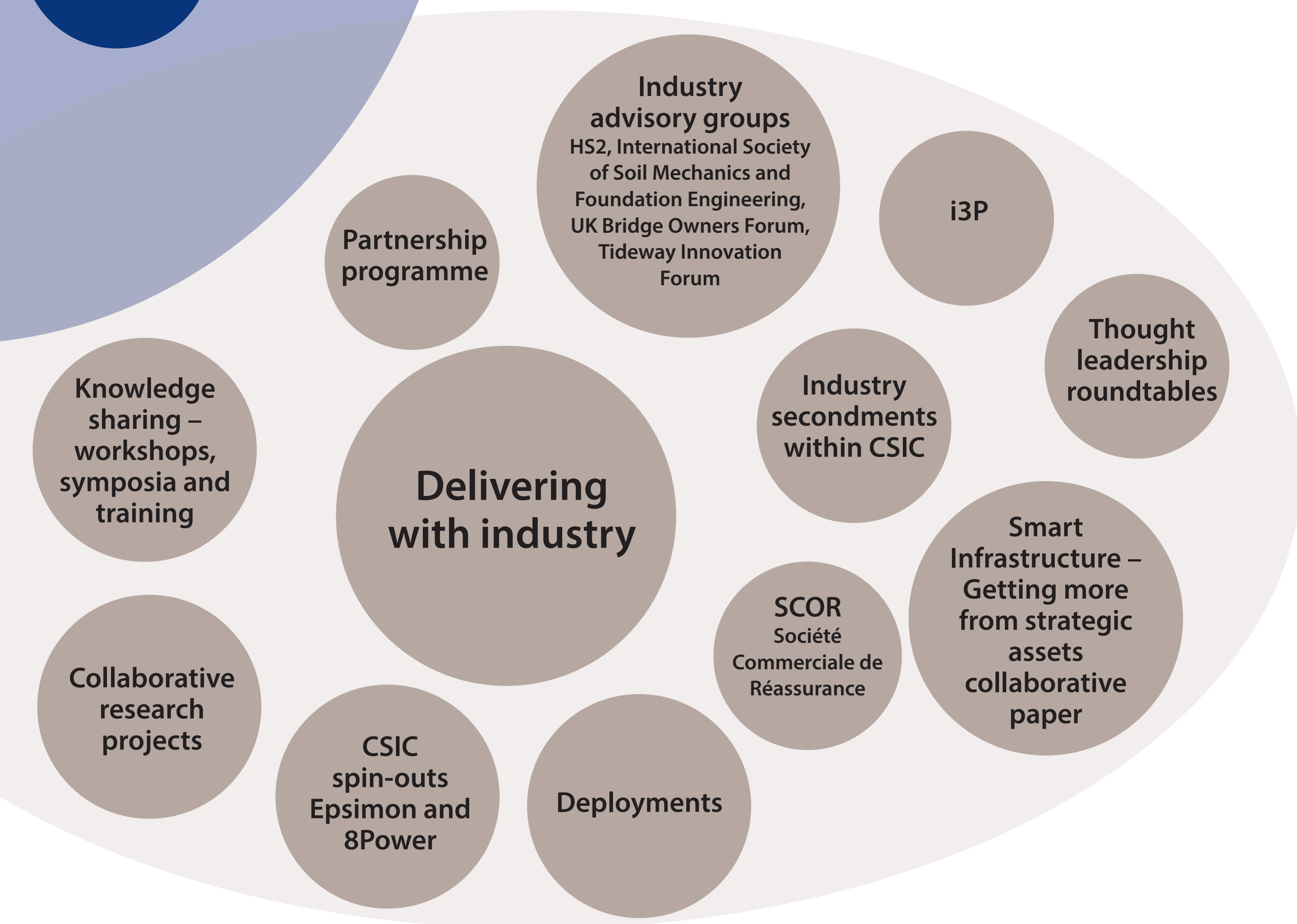
Working with CSIC creates a range of benefits derived from a strategic collaboration between academia, industry and policy. This can lead to significant progress in delivering greater efficiency in design and performance, a low-carbon society, sustainable urban planning and management and improved productivity.

If you would like to find out more about how we work or how to collaborate with us please contact:

Business development
Phil Keenan
ptk23@cam.ac.uk

Partnership
Dee Dee Frawley
ddf21@cam.ac.uk

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



Crossrail - Construction Phase Services

Thomas Graham_Arup

Data as an engineering tool for smarter decisions

Improving the whole-life performance of both new and existing infrastructure is critical to the wellbeing of the economy and social health of the UK. World-leading multi-disciplinary research from the University of Cambridge combined with advances in digital technology and accompanying abundance of data bring unprecedented opportunity for innovative integrated solutions to industry challenges.

Data enables insights into how our infrastructure is performing, how we are using it, whether it is fit for purpose, now or in the future, and what new infrastructure we may need to invest in. Data supports more efficient and sustainable design and informs better decision-making for the whole-life management of infrastructure systems and assets.

The following five CSIC case studies bring focus to the use of data as an engineering tool to enable smarter decisions about how we design, build and manage our infrastructure.

Case study 1
The virtual lab: data-led decision-making to optimise economic growth and development

Case study 2
Road degradation: a city-scale model to inform efficient asset management and maintenance

Case study 3
The observational method: data as a tool for better geotechnical engineering decisions

Case study 4
Fibre optic sensing systems for safer real-time rockfall monitoring of rail cuttings

Case study 5
Developing the supply chain to advance dynamic strain sensing

The virtual lab: data-led decision-making to optimise economic growth and development

Richard Marsham - RMG Photography

Modelling for future planning options

CSIC Investigator Dr Ying Jin from the Martin Centre for Architectural and Urban Studies, Department of Architecture at the University of Cambridge, heads the Cities and Transport Research Group. He is currently leading a three-year 'Cambridge Futures 3' modelling study, funded by Cambridgeshire and Peterborough Combined Authority and Cambridge Ahead, to design and examine alternative scenarios of workplaces, housing and transport to 2031 and 2051. The model is helping to foresee the effects of future planning options for Greater Cambridge and the project will continue to support the local land use and transport plan for a further three years.

Areas of economic growth, where enterprise and employment are flourishing, often find housing and infrastructure unable to keep pace. Disparity between these elements can lead to high house prices, congested roads from in-commuting and social inequality. Sustainable growth can be strategically supported by a long-term development plan that brings balance to business growth, the natural environment and quality of life.

Greater Cambridge case study

Greater Cambridge is an economic hot spot where growth has outpaced the rest of the UK throughout the past decade; the proliferation of high-tech businesses, innovation networks, start-ups and entrepreneurs has led to an expansion in jobs and businesses in the region. Currently around 60,000 people work in 4,700 knowledge-intensive companies in Greater Cambridge, particularly in computer and software, life sciences, hi-tech manufacturing and AI.

This economic success story is not without cost: house prices have soared – the city's average house price is now 16 times the median salary – and the think tank Centre for Cities reports Cambridge as the least equal small city in the UK. If employment continues to rise at the current rate the resulting increase in commuting will put untenable pressure on already-congested roads. The Cambridgeshire and Peterborough Independent Economic Review (CPIER) Final Report (Dr Jin was on the Technical Board for the CPIER), published in September 2018, presented its findings to the Cambridgeshire and Peterborough Combined Authority responsible for local strategic transport and infrastructure. It warns that Cambridge is at a critical point in its development and must choose between reshaping for growth or stagnating and losing its economic dynamism.

> Modelling by LUISA shows how jobs, housing demand and travel connect together, and this helps local communities make sense of what interventions will work well.

Dr Ying Jin, Lead of the Cities and Transport Research Group and CSIC Investigator

Data-led decision-making

The Cambridge Futures 3 model uses data on buildings, green spaces, housing, jobs, businesses, shops, services, schools, means of transport, congestion, crowding on trains, rents, wages, prices and perceptions of wellbeing. Threading all the different strands of information together, the computer model, LUISA, provides a new 'lens' that is otherwise unavailable to look at future working, living and travelling in and around Greater Cambridge.

Coordinated interventions

LUISA has the ability to process developments in housing, transport and jobs as one integral system and has been tested using three decades of data and knowledge on business and consumer behaviour. It models different trajectories for the region which comprises cities, market towns and Fenland villages with growing connections to Cambridge. These scenarios provide opportunities to explore long-term consequences of decisions made now around building houses, location of housing in relation to places of work and how this affects transport and commuting, living costs, rents, prosperity of companies and wellbeing of citizens. This detailed modelling provides a big picture of how jobs, housing demand and travel connect together which helps decision-makers understand what interventions will work best and how to coordinate them.

Modelling uncertainties

LUISA addresses the challenge of forecasting despite uncertainties such as politics, the economy, disruptive technology, migration and climate change by separating out what is hard to predict from the highly predictable elements. The uncertainties are then examined using a wide range of possible scenarios. When there is a balance between jobs, transport and housing, then business productivity and wellbeing of residents go up. When the balance is lost businesses recoil from thoughts of further investment costs and residents face a higher cost of living.

Balancing outcomes

The research team started LUISA modelling with a 'business as usual' case where the region develops according to current trends in employment growth and local plans for housing. This scenario showed that even a small rise in jobs would lead to considerable wage pressure in Cambridge and South Cambridgeshire and an unmanageable amount of in-commuting which would choke growth. Potentially businesses may respond to high wages and increased prices by reassessing plans for new investment or moving out of the UK to other knowledge-intensive areas overseas, resulting in a significant loss of jobs and output for the UK.

LUISA was then used to consider alternative courses of action to achieve the optimum potential for the region. Instead of asking the mathematical model what the best solutions are, which is, by definition not a question that a model can answer, LUISA is used to test scenarios that represent a full range of different courses of action, and investigate the potential effects, both positive and negative:

- Densification – inserting new sites of employment and housing within the city boundaries: this can accommodate the largest amount of jobs and people around existing and new rail hubs, but could risk worsening congestion and air quality in spite of convenient public transport access
- Fringe growth – extending urban areas around the edges of the city: this brings the highest financial returns with more modest building construction costs, but needs to use Green Belt land and will increase car use
- Dispersal – encouraging growth to go to market towns or newly created settlements beyond the Green Belt: this could spread the growth and gain social and environmental benefits, but would rely on companies that are willing to move away from current centres of high buisness productivity
- Transport corridors – developing new sites for jobs and housing along existing and new fast public transit services that emanate from Cambridge: this offers space for continued growth of existing business clusters while unlocking potential of new sites that could attract growth, but this requires the highest financial investment in transport infrastructure and services.

Improved decision-making

The main benefit of studying the four scenarios above is the opportunity for all stakeholders to be clear about their strengths and weaknesses, negotiate the difficult trade-offs, and coordinate a blended approach that addresses the concerns of the local communities. How to make that blend would be subject to a democratic process in which all residents as well as businesses and local governments take part. The model's findings would also help the local communities develop a robust case for new investments in housing, infrastructure and nature conservation from central government and private investors.

The results from LUISA are shaping the district councils' new land use plans and the Combined Authority's local transport plan. Used well, LUISA can help support a novel local strategy developed to improve quality of life across the region. The techniques developed for LUISA can be applied to other regions. Currently Dr Jin's team is also working for the UK2070 Commission examining scenarios to rebalance the UK growth in jobs, housing and transport among all areas in the UK, including the devolved countries of Wales, Scotland, and Northern Ireland as well as the English regions.

Principal Investigator: Dr Ying Jin
Modelling and analytics: Dr Li Wan, Dr Kaveh Jahanshahi, Dr Jamil Nur, Dr Tim Hillel, Tianren Yang
Data and GIS: Steve Denman, Dr Xihe Jiao
Land use and transport data: Dr Mingfei Ma, Kelly C Wang
3D Modelling: Stephanie Veanca Ho, Zhou Fang, Ying Yue, Shanshan Xie
Advisers: Professor Marcial Echenique, Professor Peter Carolin

Road degradation: a city-scale model to inform efficient asset management and maintenance

The scale of the problem

Road degradation is an increasing problem for asset managers. Potholes are one of the main contributing factors and require local authorities to commit limited funding to maintenance and repairs. According to the Asphalt Industry Alliance (AIA) Annual Local Authority Road Maintenance Survey (ALARM) 2019, the total number of potholes filled in the past year (April 2018 to April 2019) in England and Wales totals 1,860,072 at a cost of £97.8m. The average cost to fill one pothole as part of planned maintenance is £39.80 compared to £65.10 for a reactive repair.

Improving asset management

A CSIC, University of Cambridge and University of California, Berkeley research project is examining the degradation of roads (evaluation considers potholes, cracks and other types of defects) with the aim of improving road asset management. Currently asset managers lack accurate methods to support decision-making on maintenance programmes resulting in an ad-hoc approach to deciding which areas of road to repair and maintain. A predictive and city-scale maintenance approach based on accurate information would allow more efficient planning, reducing the cost of works and disruption.

Pavement condition data

This research seeks to improve knowledge about local road degradation using road condition data from visual surveys published by the San Francisco Department of Public Works. This provides historical and current information on the Pavement Condition Index (PCI) of more than 12,000 street segments in the city (pavement in this context refers to road surface).

Following recent advances in road condition monitoring, resulting data is becoming available in increasingly large spatial scales and high spatial resolutions. This brings both opportunities and challenges for road management: opportunities to understand network-wide condition change and maintenance needs at high spatio-temporal resolution; challenges to efficiently analyse large amounts of spatio-temporal data to identify meaningful and usable quantification to inform maintenance and management.

Incorporating spatial and temporal dimensions

Incorporating spatial and temporal dimensions into road degradation modelling secures a system-wide understanding for asset management. There are many difficulties in producing a reliable road condition prediction model, particularly with the strong presence of measurement errors inherent in visual surveys and lack of information on crucial degradation-affecting factors including construction quality, microclimate and ground conditions. To address the issue of 'imperfect data', additional structures in the data are considered to enable further insights of the street network. This research demonstrates that a hierarchical modelling approach can be applied in a more general manner to take advantage of natural spatial structures in the street network and considers the possible correlations between nearby road sections.

Three road degradation models were designed to represent a range of modelling strategies, including a conventional approach that fits a degradation curve for each category (road material type and functional class, see Figure 1), as well as a spatial model that explicitly considers the similarities in degradation trends of neighbouring road segments.

Benefits of spatial (SP) model

The SP model coordinates degradation rates between adjacent street segments showing regions of high degradation rates in red and low in blue (see Figure 2). Results show a large part of the individual variations in degradation rates are explained by the spatially structured component but the most convincing strength of the SP model is its ability to identify high degradation rates. The SP model:

- Is able to estimate the degradation parameters for road sections with missing or erroneous observations by using information from adjacent sections
- Can visually illustrate regions where roads degrade faster than average
- Can assist asset managers to apply their attention to a smaller region.

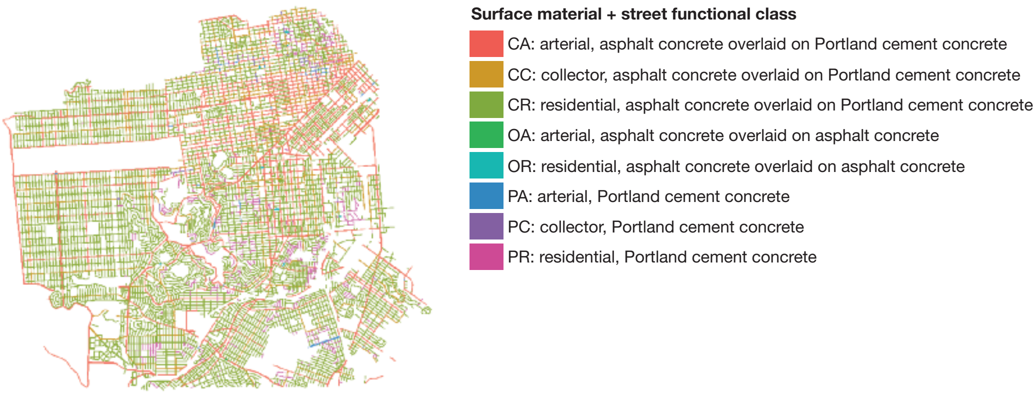


Figure 1. A diagram of street networks in San Francisco coloured by surface type and functional class category

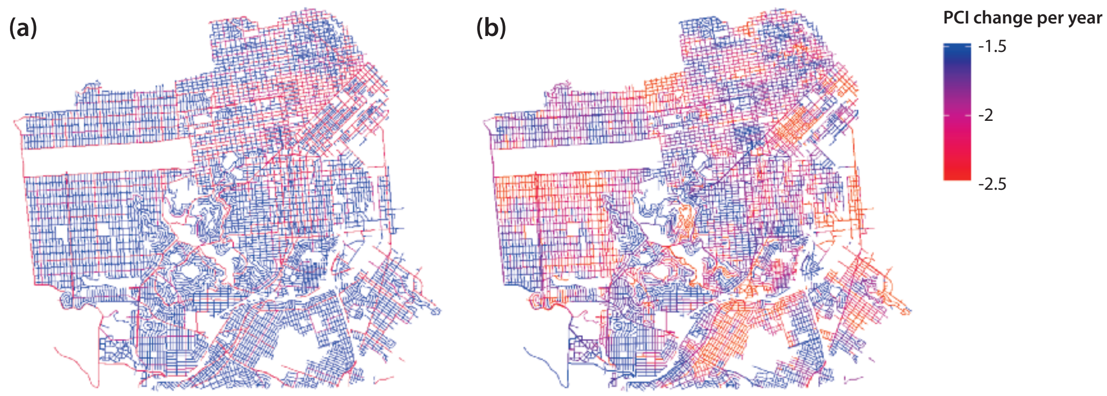


Figure 2. Map view of annual road degradation rate: (a) Road category (non-spatial), (b) Spatial model

Smart infrastructure and management

The spatial road degradation model proposed in this study emerges from recent advances in the field of smart infrastructure and management and is built on two decades of continuous records of city-scale road condition data. Such input data are premised on advanced sensing and digital data inventory technologies for road infrastructure.

This model is also an example of how interdisciplinary data analysis techniques can contribute to the management of smart infrastructure. As a basis it addresses the imperfections (measurement errors and missing predictors) in road condition data and identifies critical regions where roads tend to age faster. Such results can support local engineers to conduct more informed inspections/site investigations, and make more effective asset management decisions.

Future prospects

The spatial model can support targeted inspections to investigate underlying causes of degradation in vulnerable regions and inform asset management decisions and activities by enabling system-level maintenance planning.

Inter-disciplinary modelling for sustainable city-scale management

In the longer term road degradation and traffic simulation modelling will be brought together to consider the sustainability of the city-scale transportation system through the modelling of potential emission mitigation scenarios. Currently, there are many carbon mitigation proposals within the transportation system, for example, eco-routing where drivers choose less congested and less bumpy routes. From the infrastructure asset management perspective, the opportunities include the adoption of recycled materials, roadwork schedules to minimise construction disruptions and maintenance allocations that prioritise the reduction of use phase emissions from vehicles. Current studies of both areas remain siloed; road engineers do not consider dynamics in traffic and traffic engineers do not consider condition of roads. Taking a systems approach enables network-wide impact in reducing emissions, total vehicle hours/distance travelled and overall road conditions to better manage traffic congestion and associated pollution and inform more efficient asset management.

> Long-term asset condition performance data such as that shown in this work is extremely valuable to shift our industry from reactive maintenance to performance-based maintenance. This work shows potential opportunities to link road performance to traffic network models, leading to more sustainable road usage with system-level thinking.

Professor Kenichi Soga, Chancellor's Professor at the University of California, Berkeley and CSIC Investigator

Contact: Bingyu Zhao

The Observational Method: identifying barriers and opportunities for geotechnical engineering

The OM approach

Ralph Peck first introduced the Observational Method (OM) in the 1960s and it is most often used today as a 'best way out' process when unforeseen events occur. The method can also provide a formal way to reduce over-design in excavations and deliver projects more economically and efficiently by allowing plans to be modified before construction or during construction. Rapid redesign would then be required to provide new construction plans. CSIC Investigator Dr Giovanna Biscontin is currently exploring the potential benefits of and barriers to the OM in geotechnical engineering.

The OM in practice

The OM was formalised in the Eurocode (the 10 European Standards for structural design) in 1987 and the most recent version of CIRIA 760 (2017) clearly outlines a process for using the OM.

The four OM approaches in the CIRIA guide distinguish between the OM applied as a design tool at the start of the project ('ab initio' approach, optimistically proactive starting from most probable parameters; 'ab initio' approach, cautiously proactive starting from characteristic parameters) or as a reactive measure after construction is under way ('ipso tempore' approach, to make modifications at the time; and 'ipso tempore', reactive to make corrections).

This process for using the OM from the start of a project enables greater savings in materials and programme by reducing excessive conservatism of the initial design as construction progresses. Despite the availability of formal paths to the implementation of the OM, barriers in contractual design, monitoring, construction management (risk control, time and cost) and training mean the approach is seldom used in practice.

OM enables savings for Crossrail

In the UK, OM has been applied to a number of Crossrail deep excavations, including the head walls at Canary Wharf station, the Moorgate shaft at Liverpool Street station, the Durward Street shaft at Whitechapel station and the Western Ticket Hall at Tottenham Court Road. Before construction of the ticket hall at Tottenham Court Road station, the contractor carried out a value engineering study which identified the opportunity for an OM approach. This led to more comprehensive monitoring being installed and enabled the possibility of modifying the design at early stages through back analysis using the inclinometer data.

By the third excavation stage at Tottenham Court Road, movements were less than predicted and the most probable soil design parameters had been calibrated through back analysis, enabling the lowest level of strutting to be omitted, with the result of saving four weeks of construction time and £715,000 in cost.

OM 'ab initio' approach to maximise savings

Department of Engineering PhD student Ying Chen, supervised by Dr Biscontin, applied back analysis to the construction of the ticket hall, using three numerical approaches – FREW, PLAXIS 2D and LS-Dyna 3D. She improved the calibration of the most probable soil design parameters of London Clay for excavation design through both 2D and 3D FEM back analysis. These results can be applied to future excavations using the OM 'ab initio' approaches to maximise savings. Wall deflections as an example of the combined results of this analysis are displayed in Figure 1.

The coloured areas in Figure 1 mark confidence intervals associated with different variables, meaning that there is 95 per cent probability future observations will lie within these bounds. As more variables

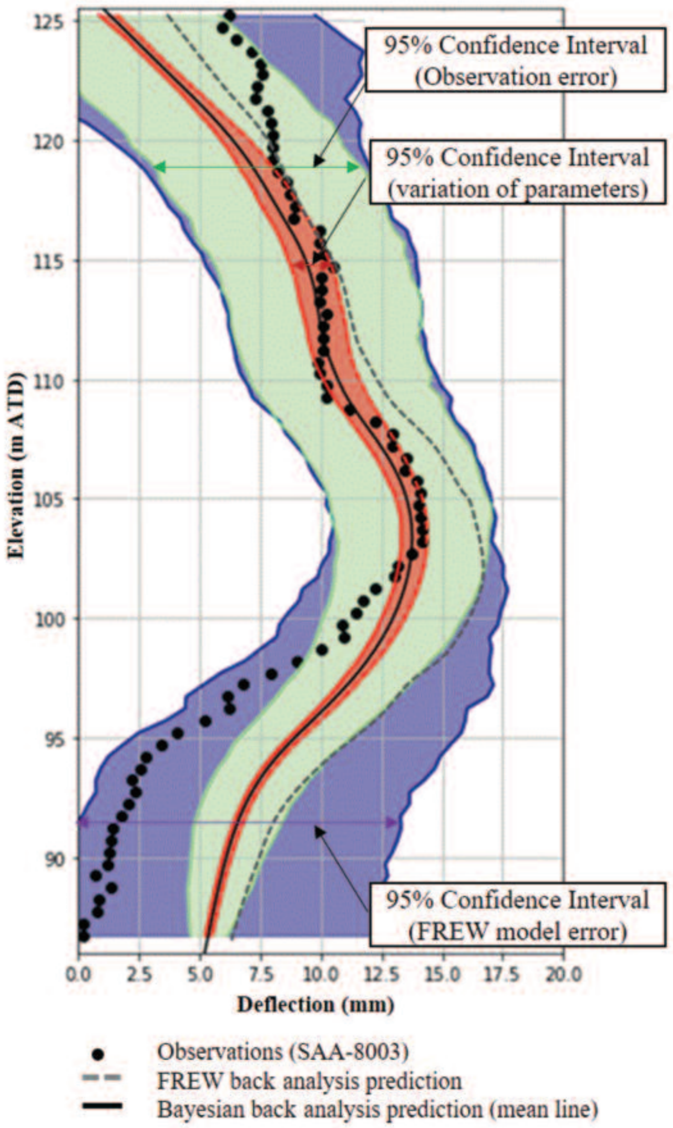


Figure 1 – Tottenham Court Road Western Ticket Hall wall deflection at the final excavation stage: observations (SAA-8003 data) versus predictions from back analysis

are incorporated into the model, uncertainties are reduced and the confidence intervals become more certain.

Barriers to and opportunities for OM applications

The potential benefits of using OM in excavations is demonstrated by the results seen in the construction of the ticket hall at Tottenham Court Road. In March 2018 Dr Biscontin hosted a workshop on 'The Observational Method for Supported Excavations: Research Challenges for Removing Barriers' at the University of Cambridge for invited industry colleagues. Attendees came from a range of organisations involved in large-scale excavation projects including designers, contractors and project owners. The aim of the CDBB-funded and CSIC-supported workshop was to define research questions to help industry overcome barriers to using the OM and provide the right tools to progress use of and benefits from the method.

ARUP Associate Director Stuart Hardy presented the four approaches to OM in the CIRIA guide and attendees at the workshop discussed the barriers and opportunities for implementing these approaches in practice:

- Contractual issues between all parties prevent implementation
- More regulatory guidance is needed for progress
- Demonstrating savings promotes interest and raises awareness
- Risk management needs to be detailed and understood by all parties
- More flexible scheduling allows for contingency plans depending on monitoring information
- Monitoring system's reliability increases confidence
- Automation of the decision-making process provides objectivity.

The workshop also covered monitoring systems for the OM, methods and processes for back analysis, and real-time analysis with statistical approaches.

Additional OM research work

The 2018 workshop discussed industry concerns about monitoring, quality of data and biased reading when using the OM. The 'most probable' parameters used in OM are vague and not sufficiently defined. Addressing this issue, Cambridge PhD student Yingyan Jin has applied machine learning techniques for a more rigorous approach to enable better decision-making in the OM. The research uses Bayes' theorem to update the probability for a hypothesis, as more evidence and monitoring data becomes available. For geotechnical engineering, the approach produces a set of parameters that provides an unbiased estimate of ground movement most likely to occur. The method can incorporate all sources of information, including prior knowledge of expert experience and site investigation. In addition, the randomness in the parameters is explicitly accounted for and confidence intervals can be drawn around mean values. This will also enable the response of the soil and excavation in the next stages of construction to be predicted and confidence intervals to be defined around the mean predicted values. As more data is fed into the process, the uncertainty is reduced and the confidence intervals become narrower. This can potentially allow a broader approach to risk assessment and a more rigorous definition of thresholds for alert levels.

The future of OM

Dr Biscontin is planning the next step for the development of research to improve the efficiency of the machine learning process when coupled with more sophisticated modelling systems to improve decision-making. As demonstrated by the Crossrail excavation at Tottenham Court Road, using OM can make a significant difference to savings in construction time and costs.

Contact: Dr Giovanna Biscontin

Fibre optic sensing systems for safer real-time rockfall monitoring of rail cuttings

Phil Keenan

Background

The Hooley Cutting, near south London, carries the main railway line from London to Brighton through the North Downs. The 30m-deep cutting slopes are susceptible to landslides and need measures to prevent rockfalls reaching the tracks, which have caused train derailments and line closures in the past.

The cutting slopes have been covered with rockfall mesh to collect any falling debris, but there have been failures behind the mesh causing the mesh to bulge towards the track. Such failures are hard to predict and a team of ground engineers is required to carry out regular inspections to monitor at-risk locations and ensure mesh integrity. A method was needed to provide an early warning of slope failures on the network.

Network Rail commissioned CSIC to devise a solution to the problem. South East Region Managing Contractor Bam Nuttall and ground engineering company Bam Ritchies joined the project team; both organisations have extensive experience of trackside installation and management. CSIC proposed using strain change that slope failure produces in the mesh, to help identify and predict problematic areas before they impact on the safety of the railway.

Innovative sensor systems

CSIC designed and trialled two different fibre optic sensing systems for the cutting. The first used discreet Fibre Bragg Grating (FBG) sensors and the second, Distributed Fibre Optic Strain Sensing (DFOS). The FBG system prepared by CSIC included a multi-channel interrogator developed by Beijing Information and Science Technology University (BISTU) and FBG strain sensors spaced 20m apart packaged in a steel armoured cable. The distributed system, manufactured by CSIC collaborator Febus (see case study 5), is a commercially available long-range dynamic Brillouin system capable of 50 measurements per second over 1000 sensing points along a 1km length. For this trial, the system was used in fast-static mode measuring all points along the length of the entire fibre sensor in 30 seconds.

BAM Ritchies engineers abseiled from the top of the cutting to fix dual cable clamps (specially designed and manufactured for this project by CSIC) to the cutting face using soil nails at fixed intervals of 20m gauge length. The sensor cables were pre-tensioned and clamped in place, and attached to the rockfall mesh along its length. The installation spanned a 100 metre width for the test location, and included four dual-rows of sensor cable from the base to the apex of the cutting.

Monitoring the cutting and data processing

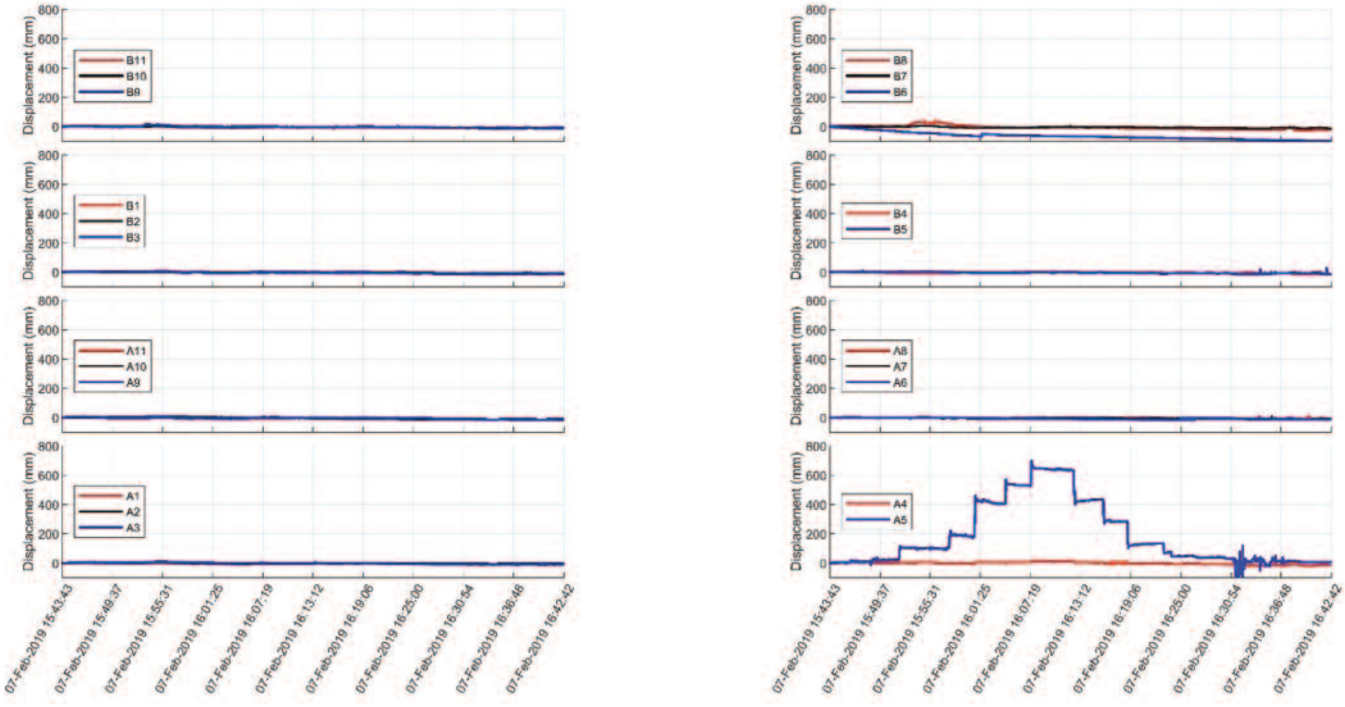
The sensor cables were routed to a control room where the two optical analysers were located. Once the system was established, the system could report the location of any change in strain of the mesh, which could indicate accumulation of debris. Dynamic measurements from the FBG sensing system were sampled at a 10Hz frequency and the raw data files from these measurements were transferred over the network for processing. This work is led by CSIC Research Associate Dr Xiaomin Xu.

In order to test the sensitivity of the system, a trial was carried out in February. The trial was carried out using a tirfor winch to lift the mesh in a controlled way. The tirfor was anchored at the top of the slope, on the crest, while its hook was attached to the mesh at a location close to the fibre optic cables. The figure below shows a snapshot of the strain change histories, measured with the various FBG sensors during the trial of the system. Each chart plots the strain measured at two or three locations on the slope. As seen, stretching of the mesh near sensor A5 results in highly localised strain, while other gauges remain mostly unaffected.

Delivery of a new practice

This project has demonstrated potential benefits for the future of rockfall monitoring. The sensor systems could replace regular inspections, so engineers would only be required to investigate locations the system has alerted them to, saving time and reducing risks. The systems could also contribute to rail safety if the sensor system was to be incorporated into an early warning system allowing better intervention and action such as alerting train drivers to the possibility of debris on the tracks.

Processing real-time digital data off-site, alongside machine learning and artificial intelligence, could also help to recognise data patterns and identify trends that are known to lead to worsening conditions. By sensing railway infrastructure, such as earthworks and embankments, assets become smart, enabling information about their state to be shared with asset owners. It becomes part of an 'internet of infrastructure', (which has the potential to transform practice, as with the Internet of Things (IoT)) by making inanimate objects interact with a knowledge system.



Real-time monitoring at Hooley Cutting.

> Network Rail is keen to investigate and assess emerging technologies for detection of rapidly moving earthworks failures in line with the Network Rail Earthworks Technical Strategy. The project at Hooley has demonstrated the potential for use of optical fibres for failure detection, increasing the options available to us for monitoring our earthworks and allowing timely detection of failures. We are keen to look at how we can best develop the application of the technology for use more widely across the network, with particular interest in the potential application for failure detection over long lengths of earthworks.

Neil Esslemont, Senior Engineer, Network Rail

Contact: Phil Keenan, 01223 748586 / ptk23@cam.ac.uk
Team: Dr Cedric Kechavarzi, Dr Xiaomin Xu and Phil Keenan

Developing the supply chain to advance dynamic strain sensing


Phil Keenan

Responding to industry call

In a working group discussion at a CSIC event, industry partners raised the subject of sensing strain in structures and that current distributed fibre optic strain sensing technologies were too slow to capture dynamic events. There was a consensus that the ability to measure strain at a rate of 50Hz or more was needed to fulfil many dynamic applications, such as capturing traffic loading effects on bridges. However, achieving this goal would require development and application of new technology.

CSIC has worked with French SME, FEBUS Optics[1] to deliver this capability. Febus had developed a new generation of fast Brillouin fibre optic strain sensing systems, the FEBUS G1. FEBUS and CSIC discussed applying the technology for civil engineering applications, and the challenge was set to create a dynamic infrastructure sensing system.

After six months of development, FEBUS met this challenge and demonstrated dynamic strain measurement at 50Hz over 1km in a fully-functioning system, the FEBUS G1D. This ability means vital performance data can be captured at sub-second rates instead of periodically sampling performance at longer time frames over several minutes. CSIC worked with Febus on minimum system requirements and specifications, and in late 2018, the FEBUS G1D was ready to leave the lab and be deployed in the field.

First deployment on a CSIC project

The FEBUS G1D was used as part of the rockfall early warning system developed by CSIC in a collaborative project with Network Rail to monitor Hooley Cutting: the steep cutting faces either side of a 170-year-old stretch of railway between London and Brighton. The FEBUS system was successfully used to monitor strain changes in a rockfall mesh in real time in order to capture potential rock debris accumulating in the mesh on the cutting (see case study 4).

Key benefits of fibre optic sensing

Optical fibre sensors can measure many infrastructure parameters, including strain, temperature, displacement, vibration, and, with some mechanical modifications, tilt and acceleration. For sensing requirements that need more than several hundred sensing points (for example embankments and rail track), optical fibre sensing also becomes the lowest cost solution. It eliminates the need for copper cable power cables or battery maintenance and is easy to install.

This ability of distributed fibre optic sensing systems, such as the FEBUS G1, to provide spatially dense information while being simple to install means that fibre optic sensors are becoming an attractive alternative to electrical point sensors for infrastructure sensing.

The system is commercially available and more than 30 FEBUS G1 systems have now been made and deployed around the world.

Implications for whole-life monitoring

The fibre optic sensor cables used by CSIC are identical to telecommunications optical fibre which has been used worldwide since the 1970s and 80s. They are made of silica which does not experience the same failure modes as electrical sensors and is one of the most environmentally stable compounds known; there is no corrosion when the sensors are exposed to humidity, nor do they suffer from electromigration ageing or copper embrittlement. They are also immune to electromagnetic fields present in high voltage environments such as rail.

Corning Glass, a leading manufacturer of optical fibre recently published a white paper on their use, and in particular, the lifespan of the product. In the paper Corning have stated that there is "no 'theoretical lifetime' of optical fibres" and that "there is no industry accepted 'wear out' mechanism for optical fibre". They reported that it is "common for customers to report to Corning that trial fibres installed in the late 1970s or early 1980s are still in use today". [2]

Optical sensing systems which can last for the life of the asset being monitored make whole-life sensing a real option for asset management and can provide the data required to ensure the asset is fit for purpose over its entire lifetime.

Phil Keenan

FEBUS G1 – image courtesy of FEBUS Optics

> We want to demonstrate the intrinsic reliability of optical sensing and what this means for instrumentation and monitoring of infrastructure. Optical analysers are now a cost-effective choice for sensing, with huge savings in the complex installation of electrical sensors, and the majority of the cabling costs eliminated. Sensing is now real-time, and the sensors themselves can outlive the structures that they are designed to monitor.

Philip Keenan, CSIC Business Development Manager

Contact: Phil Keenan, 01223 748586 / ptk23@cam.ac.uk
Team: Dr Cedric Kechavarzi, Dr Xiaomin Xu and Phil Keenan

[1] www.febus-optics.com
[2] Corning, 2016. Frequently asked questions on fibre reliability. White Paper WP5082, April 2016 www.corning.com/opticalfibre

Optimised flexibly formed beam cast in a fabric mould as part of the ACORN project (see page 29)

Image courtesy of John Orr

Research projects

CSIC has an innovative and far-reaching research programme that aims to transform the future of infrastructure and construction. A number of research projects that CSIC is involved with are featured over the following pages. These demonstrate the wide-ranging reach and diversity of CSIC's research programme that includes wind turbine foundations in developing countries, long-term monitoring of assets and changing the culture of materials used in construction.

Research project 1
An energy efficient wireless fatigue sensor system for long-term monitoring of assets

Research project 2
Digital Cities for Change: next-generation tools for city planning and management

Research project 3
Multi-sensing structural health monitoring of a skewed masonry arch bridge

Research project 4
Automating concrete construction: digital processes for whole-life sustainability and productivity

Research project 5
A GIS-based infrastructure management system to increase resilience of terrestrial transportation networks

Research project 6
Improving foundation design for wind turbines to support sustainable energy in Africa

An energy efficient wireless fatigue sensor system for long-term monitoring of assets

Metal fatigue is one of the main contributors to mechanical failure in a range of assets, from bridges and street lamps to pipelines and power turbines. During the winter of 2015 the Forth Road Bridge – a main route for around 70,000 vehicles crossing daily between Fife and Edinburgh – was forced to close for three weeks and had traffic restrictions imposed for several months due to a fatigue-induced crack found during a routine visual inspection. Estimates suggested the closure of the bridge cost the economy more than £40m.

Metal fatigue

Fatigue is caused by recurrent loading or stress to a structure causing the formation of micro cracks further weakened by repeated cycles of stress over an extended period of time. Metal fatigue can lead to sudden fracture and ultimately structural failure, even at stresses much lower than the structure would normally withstand.

Current approaches

A widely used approach for quantifying fatigue is by measuring strain and using a well-known ASTM-standard cycle counting algorithm to identify the number of stress cycles. This information is used by civil engineers to estimate the remaining fatigue life which is key to informing effective and efficient maintenance. Common sensing technologies include vibrating wire strain gauges and metal foil strain gauges; however, their use often requires a permanent power supply, which may not be readily or easily available to all assets, or high capacity batteries which are costly and difficult to maintain.

CSIC works to demonstrate better-performing and more energy efficient sensing

CSIC researchers have designed a wireless embedded sensor system that combines a novel low-power analogue electronics design and highly energy efficient software to deliver a monitoring technology that does not require mains power, allows for continuous fatigue monitoring and is durable over prolonged timeframes. Considering every component of the system under development and improving even one of these elements results in significant added value.

This system only reports the strain-cycle information necessary to estimate the fatigue life of an asset. Increasing efficiency in this way means the system neither collects nor reports the vast amounts of data associated with current standard procedures. Low-power wide area network (LPWAN) technology enables the sensors to transmit data wirelessly over long distances for long periods.

Experiments comparing the CSIC prototype with a conventional system with similar hardware characteristics to test the performance of the novel system showed a 9-fold increase in energy efficiency. Using a single 3.6V 19 Ah Lithium battery would power the conventional system for two to three months, whereas the CSIC solution will run for nearly two years. This solution is cheap to build and does not require additional cables and equipment associated with conventional systems.

The energy efficient wireless fatigue sensor system is ready to be deployed on a live site. CSIC is interested in hearing from organisations with suitable projects for potential collaboration.

> “Powering a sensor system to monitor dynamic performance of our infrastructure over the long-term is one of the greatest challenges to achieving the vision of smart infrastructure. This work shows that we can overcome this challenge by integrating state-of-the-art hardware and software tightly together. The data obtained from this system can lead to a new way to manage our infrastructure for significantly longer periods of time.

Professor Kenichi Soga, Chancellor’s Professor at the University of California, Berkeley and CSIC Investigator

Contact: Dr Xiaomin Xu
Team: Dr David Rodenas Herráiz and Dr Xiaomin Xu

Digital Cities for Change: next-generation tools for city planning and management

The challenges for modern cities to deliver smart systems for its citizens are complex and cut across many traditional disciplines. CSIC's Digital Cities for Change project, funded by the Ove Arup Foundation and the Centre for Digital Built Britain, evaluates both the existing structures and systems of city and infrastructure management, and investigates how digital tools can help better decision-making within these areas.

Understanding limitations of the current approach

The planning, management and operation of assets, buildings and towns have traditionally operated in professional silos. Researchers are investigating the impact of these silos within city and infrastructure management and how this leads to departments following separate, and sometimes divergent, approaches to address common challenges.

We live in an era of increasing digital abundance, but industry and city governments lack the tools to understand and interpret the data to support smarter decision-making processes and deliver best value from them. In order to deliver on the transformative potential of this digital revolution, we need built environment professionals who are trained in a broader range of disciplines and tools, bridging infrastructure and city management solutions and developing the opportunities presented by the digital economy.

Working with local authorities

The use of data has huge potential to help deliver social, economic and political goals for cities. Digital Cities for Change researchers have built a working partnership with Smart Cambridge, a programme supported by Connecting Cambridgeshire, which is led by Cambridgeshire County Council, and are using the city as a pilot.

A workshop was held in December 2018 with officers from the council's transport, sustainability and planning departments to plan how digital technology and data can be used to support decisions and make improvements.

The aim of the workshop was to understand the current activities addressing two of the council's policy goals; improving air quality and reducing congestion, including the use of data to support policy measures related to the goals and to explore future requirements.

Researchers are also aiming to understand the possibilities for developing a digital twin prototype for the city which responds to imminent challenges and the delivery of the policy goals.

Developing a new digital strategy

The Digital Cities for Change team is now exploring the potential building blocks of a new digital strategy, with two key components:

1. A digital twin, combining traditional urban modelling techniques, new data sources and advanced data analytics, to support decision-making in different sectors.
2. A new governance framework which will ensure successful implementation through linking planning, management and operation.

The digital twin prototype will use technology and data to tackle air pollution and traffic congestion. It will include recent trends of journeys to work in Cambridge, including how people of different ages and employment status travel to work and how different factors affect their travel. It will also explore future possible journeys to work based on transport investment, housing developments and how flexible working and new technology may impact commuting. A web-based modelling platform will also visualise future development options and give people an opportunity for feedback.

The governance aspect of the strategy will map stakeholders of the digital twin and their relationships to each other across government and private sectors. It will incorporate legislation and regulation, sharing and security. A crucial part of the governance will be citizen engagement – to connect the physical to the data and provide evidence that can motivate people to change their behaviour. This will involve talking to employees about flexible working and community co-working spaces.

The vision for the city-level strategy

The Cambridge digital twin prototype, along with the governance recommendations is under development, with an initial version discussed with colleagues at Smart Cambridge in April. The project team is now planning to refine the strategy and develop the tool to explore different aspects of the collection, processing and use of data to improve various city functions.

> The vision for the digital twin is to become the next-generation tool for smartening city planning and management. It is crucial to use digital technology to deepen our understanding of cities and urban societies. This knowledge will enable us to take advantage of opportunities, while recognising limitations and taking pre-emptive measures to contain the possible risks.

Dr Li Wan, Lecturer, Department of Land Economy, University of Cambridge

Contact: Dr Timea Nochta
Team: Dr Li Wan, Nicole Badstuber, Noura Wahby, Dr Jennifer Schooling and Tianren Yang

Multi-sensing structural health monitoring of a skewed masonry arch bridge


Matt DeJong

Skewed masonry arch bridge

In 2018, Network Rail commissioned CSIC and AECOM to install structural health monitoring technologies on a skewed masonry arch bridge in North Yorkshire, which had suffered extensive historic damage. The technologies would monitor how the 150-year-old bridge behaved structurally and how it was responding to intervention work carried out in 2016. Network Rail also wanted to explore available monitoring technologies to determine which ones worked well and could be used on other assets. The system traditionally used in the UK is deflection pole monitoring, which measures vertical crown displacements at the arch soffit under the centre of the tracks above. However, this method often entails difficulties with access and may require costly and disruptive road closures.

Bespoke monitoring system

Following several desk studies, laser vibrometry and laser scanning at an initial monitoring visit, engineers were able to study the environment of the bridge and design a bespoke monitoring system. The vibrometry was used to provide an initial gauge of the magnitude of movements that the bridge was experiencing under typical train loading. The laser scan data was used to profile the surface of the bridge and to decide the locations of monitoring equipment, given the constraints of an A-road and footpath running underneath it.

CSIC installed distributed monitoring technologies, including a network of fibre optic Fibre Bragg Gratings for detailed dynamic measurement of strains across the arch, a laser scan analysis of historic deformations, and videogrammetry to capture dynamic displacements. AECOM installed an autonomous remote monitoring system comprising a range of dynamic, point-sensing technologies. Real-time monitoring with this system allows for accurate tracking of long-term trends in the monitoring data.

The bridge was monitored for six months from September 2018 to February 2019. Both teams from AECOM and CSIC analysed large quantities of data to co-author a series of reports for Network Rail. The reports summarised the studies undertaken before installation, the reasons the system was chosen, the evaluation of the technologies used, and the results to date. An upcoming report will also provide guidance on monitoring technologies that can be used as alternatives to the deflection pole method.

Next steps

Following internal review by the client, it is intended that these reports will be submitted to the European Shift2Rail programme as examples of research that Network Rail is supporting. Network Rail is also commissioning AECOM and CSIC to perform long-term monitoring of the bridge, which demonstrates the value of the installed monitoring system and the benefits of long-term structural health monitoring. As part of this, the CSIC FBG system will be upgraded to be autonomous and self-sufficient, running on solar power in the same way as AECOM's remote point-sensing system. This enables FBG measurements to be taken automatically and monitoring data transferred back to the CSIC office for analysis. The teams from AECOM and CSIC have also been invited to present the project results to other asset engineers at Network Rail as an example of best practice.

This project has enabled CSIC to continue the development of fibre optic monitoring of heritage structures and carry out research into the fundamental behaviour of an existing skewed masonry arch railway bridge. Following refinement of the monitoring system at this bridge, it is expected that more testing on other bridges will take place in the next year.

Contact: Dr Matthew DeJong, University of California, Berkeley
Team: CSIC: Sam Cocking, Dr Haris Alexakis, Jason Shardelow. Network Rail: Sam De'Ath. AECOM: David Kite and Daniel Thompson

Automating concrete construction: digital processes for whole-life sustainability and productivity

CSIC Investigators are collaborating with colleagues from the Universities of Bath and Dundee to drive a new culture in the construction industry to improve whole-life sustainability and productivity. CSIC is a project partner and Director Dr Jennifer Schooling chairs the steering group.

Automating Concrete Construction (ACORN) is one of four research and development projects funded by UK Research and Innovation (UKRI) under the Industrial Strategy Challenge Fund 'Transforming Construction'. The three-year project will address the core aims of the programme: designing and managing buildings through digitally-enabled simulation and constructing quality buildings through offsite manufacturing approaches.

ACORN aims to create a culture that takes a holistic approach to the manufacture, assembly, reuse and deconstruction of concrete buildings. This will lead to a healthier, safer built environment and a culture that is built on the concept of using enough material, and no more.

The challenge

Today, the widespread use of flat panel formwork for concrete leads to materially inefficient prismatic shapes for the beams, columns, and floor-slabs in 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 much as half of the concrete in a building could be saved, if only we approached the use of the material in a different way.

Optimised concrete

Concrete starts its life as a fluid and can therefore be used to form structures of almost any shape, given the right mould geometry. ACORN will capitalise on this material property to drive the minimisation of embodied carbon in new building structures. The team will create an end-to-end digital process to automate the manufacture 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. Something as simple as allowing beams, columns and floor-slabs to have the shape they need to take load, rather than the shape they need to be easily formed, allows a complete rethink of the way material is used in buildings.

Fabrication of concrete elements

By moving the manufacture of structural concrete elements into a highly controlled factory environment, ACORN aims to ensure that buildings can become more sustainable and the construction industry more productive. Considerations such as the materials to be used, how reinforcement is placed efficiently, how to take into account whole-life value, and how to organise the design process to take advantage of the new possibilities of robotics, will all be considered within the sphere of the project.

Demonstration building

The key to transforming this conservative industry is to lead by example. One of the most exciting parts of the project, is the proposed construction of two bays of a full-size prototype office building, to be completed at the BRE Innovation Park in Watford. One bay will be left with an exposed structure to show the methods and techniques used in its manufacture, the other bay will be fitted-out as an office building, with roof, walls, façade and internal finishings, to show how the techniques translate into an architectural solution.

The demonstration building will serve multiple purposes. On an academic level, it will contribute to the research agenda by acting as a living laboratory. Embedded sensors will collect and share useful live data about how the building is performing structurally, as well as what loads the different parts are carrying. The BRE Innovation Park is visited by 20,000 people annually and data will also be collected from those visitors in user surveys, to evaluate the new appearance. The building's eventual deconstruction will also be an opportunity to verify how the whole-life value drivers for automation perform in reality.

Benefits

The ACORN project is expected to produce a number of benefits. Reducing reliance on concrete will have a positive environmental effect – construction accounts for nearly half of the UK's carbon emissions and concrete alone for five per cent of global CO_2 emissions. There is also huge cost-saving potential – ACORN's research has identified close to £4bn in cost savings for UK construction per annum, that would arise directly from better consideration of material use. Globally, a mere one per cent reduction in construction cost would save $100bn annually. ACORN's focus on automated manufacturing and digital processes to reduce both fabrication and build time are key parts in realising better value.

The project will benefit from the contributions of 12 industry partners, including architects, engineers and building contractors, who will work alongside the ACORN team to ensure outputs will bring value to industry. The professions will also benefit with architects able to explore a new form of construction; engineers gaining insights into the real loads such structures have to carry during their lifetime; and contractors having the tools they need to increase quality control, productivity and fabrication time, while de-risking the construction site.

> ACORN is tackling the UK government's Construction 2025 targets head-on. By automating construction, moving it off-site, and developing a culture of using just enough material, and no more, the project will lower costs, reduce delivery times and dramatically reduce carbon emissions.

Dr Paul Shepherd, Principal Investigator and Senior Lecturer at the University of Bath

Contact: Dr John Orr
Team: Bath: Dr Paul Shepherd, Professor Tim Ibell. Cambridge: Dr John Orr, Dr Ajith Parlikad. Dundee: Dr Saverio Spadea

A GIS-based infrastructure management system to increase resilience of terrestrial transportation networks

Modern society is increasingly dependent on transportation networks. The ability of our transport systems to function during adverse conditions and quickly recover to acceptable levels of service after an extreme event is fundamental to the wellbeing of citizens and strength of the economy.

The SAFEWAY project

The SAFEWAY project, a GIS-Based Infrastructure Management System for Optimised Response to Extreme Events on Terrestrial Transport Networks, aims to address the ability of transport systems to function during adverse conditions and quickly recover to acceptable levels of service after extreme events. SAFEWAY develops a transversal solution mainly focused on terrestrial transport modes, including both roads and railway infrastructure networks. Several of the SAFEWAY modules (mainly monitoring and risk prediction) can also be applied to other transport modes such as maritime.

The main objective of the project is to design, validate and implement holistic methods, strategies, tools and technical interventions to significantly increase the resilience of inland transport infrastructure by reducing risk vulnerability and strengthening network systems to extreme events. The University of Cambridge is one of 15 partners collaborating on the project, which is being coordinated by the University of Vigo, Spain.

Challenges addressed

SAFEWAY project tools and interventions will be deployed for critical hazards, both natural and man-made, including: wildfires in Portugal; floods, which currently account for half of climate hazards across Europe; land displacements in the UK, Spain, the Netherlands and Portugal; and seismic-related events in the Iberian Peninsula and Italy. Resilience to man-made hazards such as terrorism, vandalism, accidents, and negligence will be secured by mitigating their impacts with real-time mobility advice, such as TomTom real-time traffic management. SAFEWAY also employs innovative socio-technical elements of psychology and risk tolerance for communities at local, regional and European level, for both natural and man-made hazards. SAFEWAY's objectives will address and strengthen the four criteria for a resilient infrastructure: robustness, resourcefulness, rapid recovery and redundancy.

Optimum balance

Senior Lecturer in Industrial Systems at the Institute for Manufacturing and CSIC Investigator, Dr Ajith Parlikad, is leading collaborative research to develop predictive models for critical infrastructure assets that consider measured structural performance and trends observed in large databases to estimate the risks of future infrastructure damage, shutdown and deterioration. Projections of second, third-order, and long-term consequences will also be assessed. The University of Cambridge team will be involved in the development of a robust decision support framework for terrestrial transportation infrastructure management by considering diverse types of risks related to natural and man-made extreme events and balancing stakeholders' demands and optimising priorities over asset types. The objective is to identify the optimum balance between long-term risk minimisation and available financial resources to find the optimum resilience.

SAFEWAY is funded by the EU Horizon 2020 'Smart, green and integrated transport' work programme which is aimed at achieving a European transport system that is resilient, resource-efficient, climate-and-environmentally-friendly, safe and seamless for the benefit of all citizens, the economy and society.

> “ SAFEWAY offers tangible innovation potential for industry. The new knowledge and solutions that arise from SAFEWAY methodologies, innovation and research projects will enhance the work of CSIC that fosters accelerated industrial adoption through collaboration with industry partners.

Dr Ajith Kumar Parlikad, Head of Asset Management Group, Institute for Manufacturing, University of Cambridge and CSIC Investigator

Contact: Dr Ajith Parlikad
Team: Dr Georgios Hadjidemetriou, Dr Ajith Parlikad

Wind Africa: improving foundation design for wind turbines to support sustainable energy in Africa

Talia Da Silva

Drilling taking place at a chosen site in the north-east of South Africa; an area known to pose problems to structures due to the expansive clays

The project

Now in its second year, Wind Africa is a collaborative project which aims to support the potential of renewable energy resources to generate power across the continent and is funded by the Engineering and Physical Sciences Research Council (EPSRC).

Approximately half of Africa's population lacks access to electricity and more power generation is also needed to meet future demand. It is estimated that 35 per cent of the world's resources for wind energy could be located in the continent, but there are several challenges to developing the necessary infrastructure. Arid conditions result in unsaturated soil, mostly expansive clay, which makes founding wind turbines difficult. The soil properties change throughout the seasons and with variations in moisture content; surfaces heave in the wet season and shrink in the dry season. These cycles can cause significant damage to buildings founded on these soils.

The aim of the Wind Africa project is to develop a set of design guidelines for piled wind turbine foundations in expansive clay to support growth of a sustainable energy market in Africa. There are four work packages to the project:

- To perform field tests on the cyclic response of foundations on unsaturated expansive soils
- To complement the field testing with centrifuge tests
- To perform an extensive laboratory study on samples of soils taken from expansive soil regions in Africa
- To develop a numerical analysis code to allow detailed studies to be performed on foundations with various geometries and configurations.

The first and third packages are being undertaken by researchers in Cambridge, led by Dr Mohammed Elshafie, CSIC Investigator and Senior Lecturer for the Laing O'Rourke Centre for Construction Engineering and Technology. The second and fourth packages of the project are being investigated by collaborators at the University of Pretoria and Durham University respectively.

Field testing in South Africa

In January, a geotechnical drilling investigation took place on the proposed field-testing site in South Africa. The site was chosen as there is evidence of problems with structures, which can be seen in the cracks of nearby buildings. It is also a large open area of known expansive clay with a lack of current infrastructure that would be impacted by testing.

Two boreholes were drilled to investigate the profile of the soil and samples were taken for laboratory testing. Rock was found at an approximate depth of 12m in both boreholes and slickensided material, which is evidence of expansive soil, was found throughout the profile until the transition to rock. Undisturbed soils were also taken from the boreholes for the laboratory testing in Cambridge.

Three types of testing were carried out on the soil samples; water retention, oedometer and triaxial tests to determine the moisture characteristics, stiffness and strength of the soil respectively. The samples were characterised and were found to have a high percentage of clay and a low percentage of gravel. The change in the volumes of the samples was measured during wetting and drying cycles and shrinkages recorded. Swelling tests under different stress levels are still to be undertaken and mineralogical composition investigated.

Planning is now under way for the installation of the piles for the full field testing programme.

> We are at an exciting stage of the project with the first part of the drilling completed. The design guidelines we are working towards will aid geotechnical engineers to select the most appropriate foundation solution to suit unsaturated expansive soil conditions subject to extreme weather conditions.

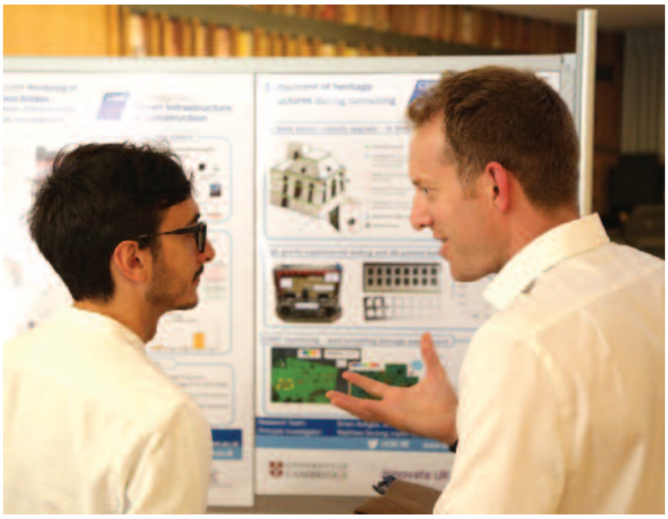
Dr Mohammed Elshafie, CSIC Investigator and Senior Lecturer in Construction Engineering for the Laing O'Rourke Centre for Construction Engineering and Technology

Contact: Dr Mohammed Elshafie
Team: Dr Talia Da Silva and Dr Khalid Alhaj Abdalla, Laing O'Rourke Centre Research Associates, Dr Mohammed Elshafie, Dr Giovanna Biscontin

Construction in Aluminium by Kenneth Martin at the Department of Engineering, University of Cambridge

Sir Cam, Twitter / Instagram: @camdiary

Impact and outreach



Raising awareness of the Centre's research is key to CSIC's ambition to transform industry. Our programme of partner-focused events share our research and policy outputs with infrastructure and construction colleagues, supporting them in finding solutions to real industry challenges. Partner organisations benefit from sharing knowledge and helping to develop CSIC's research agenda. In addition to hosting lectures, workshops and bespoke training sessions, CSIC experts contribute to many conferences, keynotes, panels and industry events.

CSIC Events

Distinguished Lecture

The 2018 Distinguished Lecture was presented by Dr Anne Kemp OBE (pictured top left), Director at Atkins for BIM Strategy and Development and Chair of the UK BIM Alliance. Dr Kemp's lecture, entitled 'A glimpse into the future... by considering the past. The challenges, the opportunities – and our consciences,' drew attention to the considerations required to make the most of data abundance to optimise the potential of smarter infrastructure.

Value of data in construction and asset management

CSIC and CIRIA (Construction Industry Research and Information Association) held an event for partners at the Institute for Manufacturing in Cambridge which focused on the value of data in whole-life infrastructure projects. A number of presenters shared research and insights from case studies and practice, including Dr Jennifer Schooling, CIRIA Project Manager Lee Kelly and Executive Director of the Centre for Digital Built Britain (CDBB), Alexandra Bolton.

Cybersecurity with CDBB

CSIC teamed up with CDBB to host a cybersecurity briefing and workshop for both users and providers of smart infrastructure solutions. The event covered the implications of cybersecurity and highlighted support and solutions available, and included presentations from government security advisors and cybersecurity experts.

CSIC Partner Summer Party

CSIC hosted its annual Partner Summer Party that combined a selection of presentations by research associates and PhD students with afternoon tea. Presentations included new analysis and monitoring tools for tunnelling-induced damage, data-centric engineering, and asset management for bridge systems. All of the presentations are available to view on the CSIC YouTube channel.

Roundtable at the GEC

CSIC held a roundtable discussion as a fringe event at the Global Engineering Congress (GEC) at the Institution of Civil Engineers (ICE) headquarters in London in October. The roundtable, 'Smart sustainability – data and information as engineering tools to mitigate climate change', included leading figures from the infrastructure and construction sector, academia, sustainability, finance, insurance, development and policy.

CSIC Partner Strategy Day

Industry colleagues joined academics for the annual CSIC Partner Strategy Day in December to identify potential collaborative projects that address real industry challenges. This year's event focused on nine themes which were generated from a call to partners for next generation challenges from their specific area of industry.

External outreach

Awards

The CSIC collaborative project, 'Monitoring heritage buildings with fibre optic sensors during the Bank Station Capacity Upgrade', has won two awards: the New Civil Engineer (NCE) TechFest 2018 Award for Research Impact: Application in the Industry; and the Innovation in Instrumentation and Monitoring award at the New Civil Engineer Tunnelling Awards. The redevelopment of London Bridge Station also won Transport Project of the Year and the ICE 200 award at the British Construction Industry Awards. The Hooley Cutting Fibre Optic Sensing project, as featured on pages 22 and 23, won the award for Best Use of Technology at the Rail Partnership Awards and was shortlisted in six categories for the Ground Engineering Awards 2019.

Trade articles

CSIC has contributed to and featured in a number of publications during the year sharing thought leadership and highlighting research. These include: the Royal Institute of Chartered Surveyors (RICS) Construction Journal; Journal of the Chartered Institution of Civil Engineering Surveyors and their annual publication Geospatial Engineering; BIM+; Tunnelling Journal; New Civil Engineer; and Infrastructure Intelligence.

Journal of Smart Infrastructure and Construction

In addition, Dr Jennifer Schooling, Director of CSIC, and Professor Kenichi Soga, Chancellor's Professor, University of California – Berkeley, USA and CSIC Co-Investigator, co-edit the Journal of Smart Infrastructure and Construction (SMIC). This journal facilitates the development of a professional community of academics and practitioners to apply and adopt the technologies, concepts and solutions to deliver smarter infrastructure construction and management.

.Visits to and featuring CSIC

The Centre has hosted delegates from a range of national and international organisations this year. The Exchequer Secretary to the Treasury, Robert Jenrick (MP) (pictured above, centre) visited in July 2018 in a joint event with CDBB to see a selection of CSIC's innovative and emerging technologies. Dr Jennifer Schooling and a number of our research associates also presented projects at an event for the Department for Business, Energy and Industrial Strategy (BEIS) at CDBB in February 2019. We were pleased to host six international delegations across the year

Ove Arup Foundation 'Catalyst for Change' exhibition

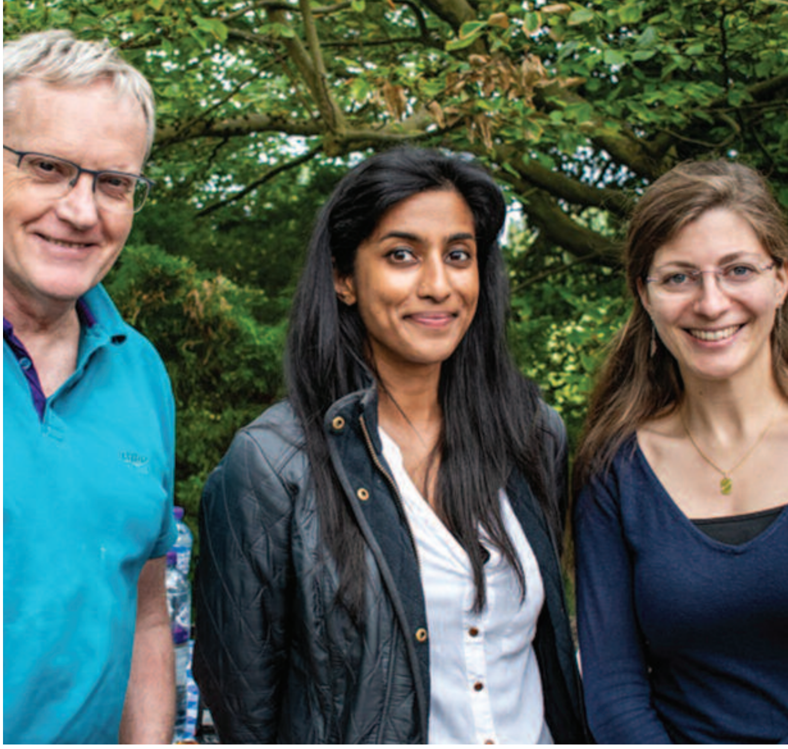
The Ove Arup Foundation celebrated its 30th anniversary with an exhibition entitled Catalyst for Change, featuring some of the grants it has given for projects involving interdisciplinary design practices for the built environment. The CSIC project, Digital Cities for Change, was chosen for the exhibition and a film was made with Research Associates Timea Nochta and Li Wan, which is available to watch on the Ove Arup Foundation website.

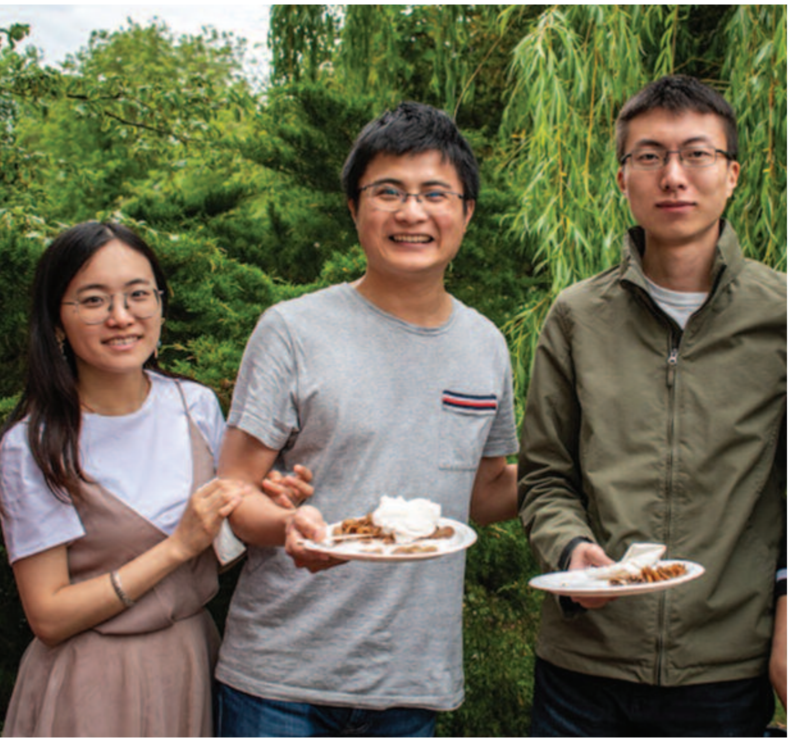
Cambridge Science Festival

More than 1,000 people visited the Department of Engineering for the annual Cambridge Science Festival in 2019. CSIC hosted 'Smart Building, Smart Construction' in collaboration with the Laing O'Rourke Centre for Construction Engineering and Technology as part of the event. A range of smart technologies were showcased including: an instrumented suspension bridge that demonstrated dynamic strain; a CSIC-developed data acquisition system featuring acoustic emission sensors and an accelerometer that displayed a real-time signal on contact with the sensor; and the mixed reality world of the Microsoft Hololens.

Institution of Civil Engineers Invisible Superheroes Exhibition

Following the CSIC contribution to the Tunnel Engineering Exhibition at the Institution of Civil Engineers (ICE) in 2017, which included a short film and presentations of sensing devices, the Centre was invited to contribute to the Invisible Superheroes Exhibition which was open throughout 2018 and is now available online.






STAFF

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
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
Francine Bennett
Mastodon C
Dr Keith Bowers
COWI (formerly TfL)
Professor John Burland CBE (Chair)
Imperial College London
Volker Buscher
Arup
Robert Dean
HS1
Tim Embley
Costain
Tom Foulkes
Independent Consultant
Steve Hornsby
Independent Consultant
Adam Locke
Laing O'Rourke
Professor Andrew McNaughton
HS2
Vlad Palan
Highways England
Richard Ploszek
Infrastructure and Projects Authority
David Pocock
Jacobs
Stephen Pottle
WSP
Dr Scott Steedman CBE
British Standards Institution (BSI)
John St Leger
HS2

Investigators

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, 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 Centre Lecturer in Construction Engineering
Dr Ying Jin
Senior Lecturer in City Planning, Urban Design and Modelling
Dr Dongfang Liang
Lecturer in Civil Engineering Fluid Mechanics
Professor Duncan McFarlane
Professor of Industrial Information Engineering
Professor Campbell Middleton
Laing O'Rourke Professor of Construction Engineering
Dr John Orr
University Lecturer in Concrete Structures
Dr Ajith Parlikad
Senior Lecturer in Industrial Systems
Professor Ashwin Seshia
Professor of Microsystems Technology
Dr Elisabete Silva
Senior Lecturer in Spatial Planning
Professor Kenichi Soga
Chancellor's Professor, University of California, Berkeley
Dr James Talbot
Senior Lecturer in the Performance-based Design of Structures
Professor Giulia Viggiani
Professor of Infrastructure Geotechnics
Dr Matthew DeJong
Assistant Professor Structural Engineering, Mechanics and Materials
(now at University of California, Berkeley)
Dr Christelle Abadie
University Lecturer in Civil Engineering
Dr Sam Stanier
University Senior Lecturer, Geotechnical and Environmental
Research Group

Staff

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
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 Quichen Lu
Dr Timea Nochta
Dr David Rodenas Harráiz
Dr Yi Rui
Dr Talia da Silva
Dr Li Wan
Dr Xiang Xie
Dr Xiaomin Xu

Research Assistants
Nicole Badstuber
Noura Wahby
Tianren Yang

Research Students
Sam Cocking
Kasun Kariyawasam-Katukoliha-Gamage
Gianluigi Della-Ragione
James Heaton
Melanie Jans-Singh
Vanessa Di Murro
Zeng-le Ren
Sakthy Selvakumaran
Jason Sun
Simon Ye
Mingda Yuan
Bingyu Zhao

We would like to thank everyone who has contributed to another successful year at CSIC, our Partners, International Advisory Group, Steering Group, and former staff. In particular, we would like to thank Steering Group members Professor John Burland, Tom Foulkes, David Pocock, Stephen Pottle and Vlad Palan for their invaluable input to this review.

The National Research Facility for Infrastructure Sensing

Giulia Viggiani
Professor of Infrastructure Geotechnics
CSIC Investigator

In July, the Civil Engineering Division will move to its new home on the West Cambridge site. CSIC, along with the Laing O'Rourke Centre for Construction Engineering and Technology, and the Geotechnical and Structures Groups will benefit from a designed-for-purpose new building with world-class laboratory facilities. The new National Research Facility for Infrastructure Sensing (NRFIS), part of the UK Collaboratorium for Research in Infrastructure and Cities (UKCRIC) portfolio, will also be housed in the building.

NRFIS will bring together engineering facilities and sensor development capabilities to meet the cross-disciplinary needs of civil engineering, infrastructure design, construction, operation and asset management. The facility offers an interdisciplinary space to develop sensors and instrumentation for infrastructure monitoring and assessment, spanning scales from an individual asset, such as a tunnel, building or bridge, to a complex system such as a railway network or city district. NRFIS will focus on the research and application of advanced sensor technologies to enable the design, construction, and maintenance of the UK's existing and future infrastructure, ensuring it is resilient, adaptable, and sustainable for years to come. The world-leading research taking place at NRFIS will support the UK as a global leader of smart infrastructure, data analytics and asset management.

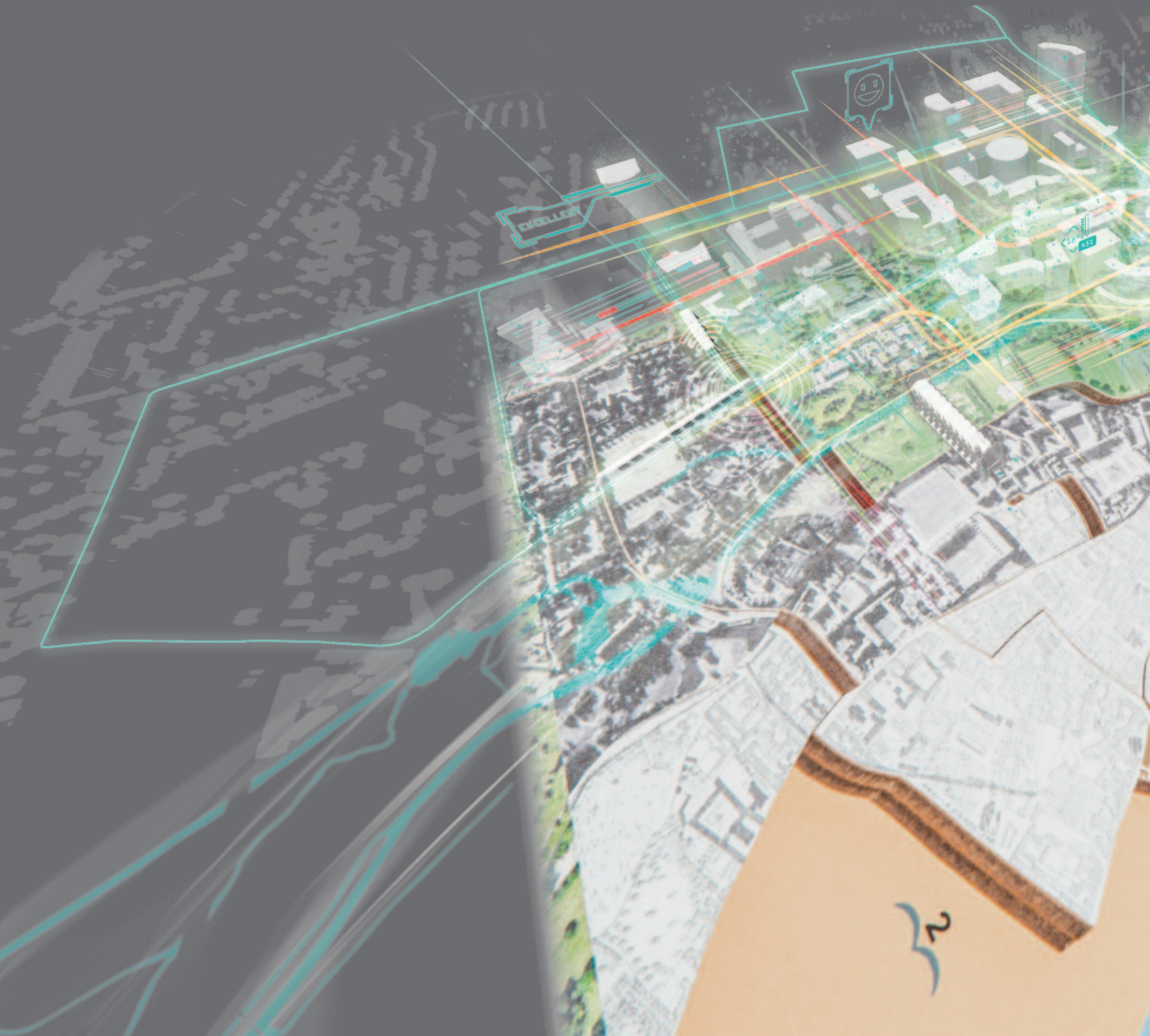
At every stage of construction, the building has been instrumented, showcasing the work of CSIC, with six sensor packages installed from the roof to the foundations. Instrumentation includes temperature sensing in ground source heat pump boreholes, embedded sensors in the basement raft and perimeter walls, in the strong floor slab, and in the frame structure. Building environment sensors assess the effect of external and internal environmental factors on the working environment and on workers' wellbeing. The blue roof instrumentation, led by Dr Dongfang Liang, monitors the weather condition, soil moisture content, water level and temperature sensors of the roof to determine its environmental effectiveness, as well as provide environmental parameters for the other sensing packages.

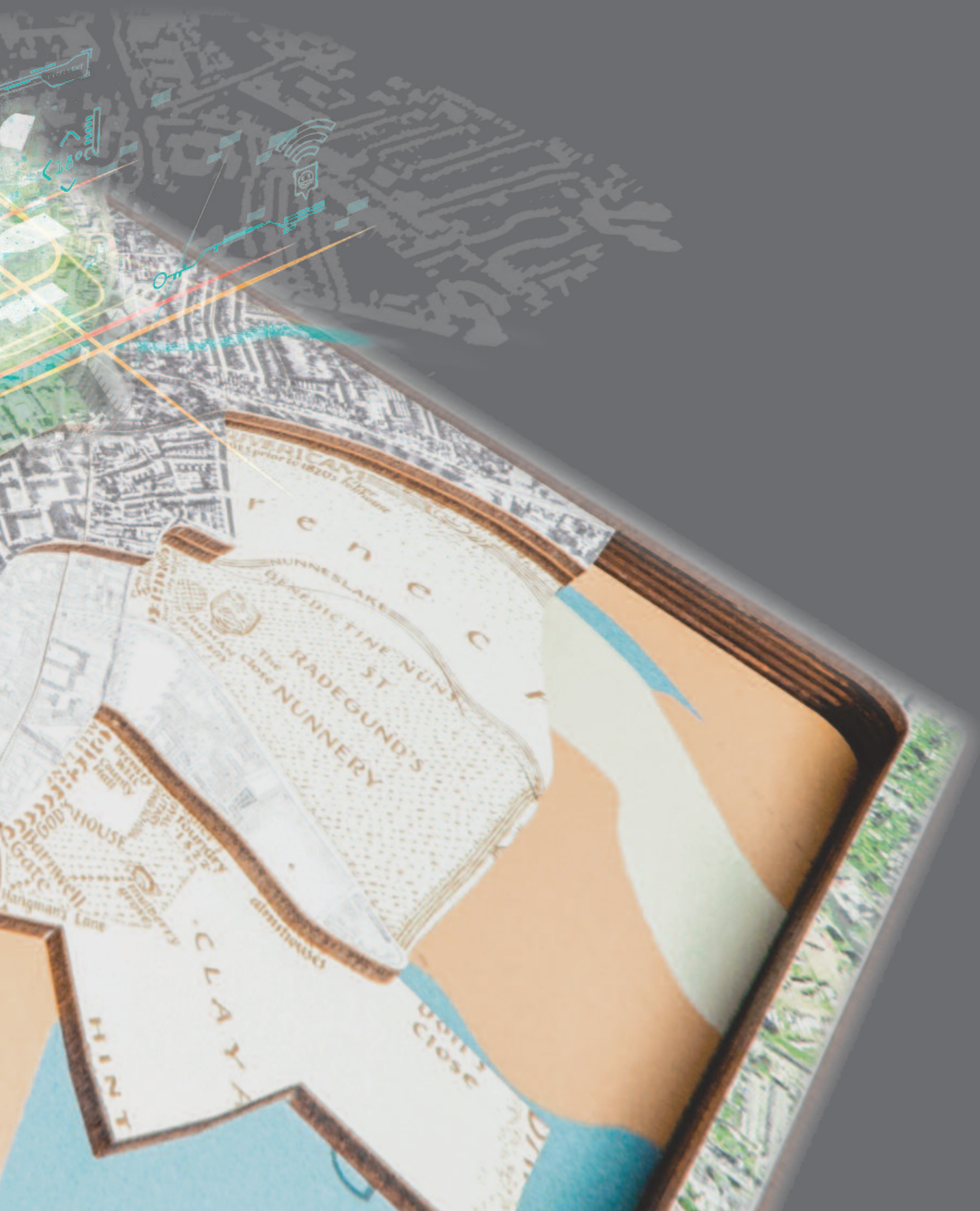
As a team, we are developing the technologies to display, store, interpret, and visualise these data streams, to understand the performance of the building and assess this performance against the predictions made during design.

As the engine for NRFIS, CSIC has brought together the expertise needed for instrumenting the building. The research facility is an excellent opportunity for CSIC to develop more cutting-edge technology, with new laboratories available to develop and apply novel sensor systems. As a CSIC Investigator, I look forward to seeing the Centre maximise these opportunities, to bring in a new era of infrastructure monitoring.

Our industry is embracing the digital revolution – we now need to transform our operational approaches to enable us to get maximum value from the data we are generating, not just for ourselves but for the generations that follow.

Dr Jennifer Schooling OBE, Director of CSIC





Title: A digital city building on a historic past

At the base is *A Cambridge Palimpsest* by artist Issam Kourbaj © 2019 www.issamkourbaj.co.uk

Palimpsest photography by Mike Thornton, StillVision Photography

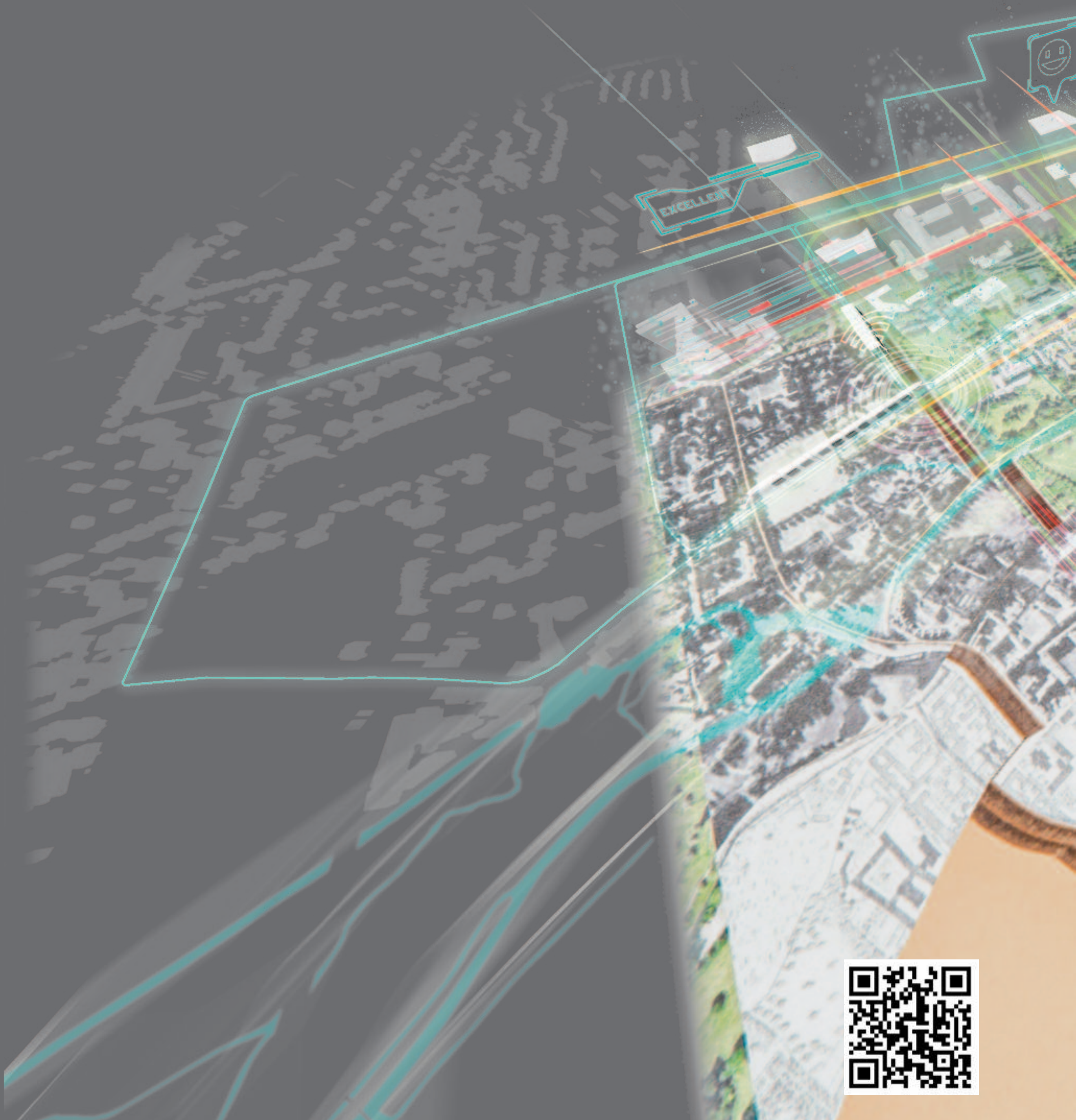
The 3D graphic addition by Stephanie Veanca Ho, Research Assistant, Department of Architecture, University of Cambridge

With thanks to Cambridge University Press for access to the Palimpsest.

Contact us

The Cambridge Centre for Smart Infrastructure and Construction
Department of Engineering
University of Cambridge
Trumpington Street
Cambridge CB2 1PZ

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



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