Innovation in sensing to monitor the influence of tunnelling under heritage structures

Introduction

CSIC is collaborating with the contractor Dragados and its monitoring arm, Geocisa, under the guidance of London Underground, to monitor the structural response of Christopher Wren's Grade I listed St Mary Abchurch and George Dance's Mansion House during major tunnelling work taking place under the buildings. The tunnelling is part of the Bank Station capacity upgrade taking place between 2016 and 2021.

Advanced engineering analysis had indicated only negligible impact is expected in each building. However, there are significant uncertainties regarding the behaviour of the ground and the buildings during the tunnelling making monitoring a necessary mitigation measure. Monitoring includes new generation sensing techniques – fibre optic strain sensing, photogrammetry, point cloud and satellite displacement monitoring. Data from these techniques are compared with data from traditional instrumentation to assess their reliability for these applications and to gain a better understanding of the response of the structures to inform future design.

Live monitoring with fibre optic sensing

Fibre Bragg Grating (FBG) strain measurement utilises a fibre optic cable with strain sensors present in-between cable attachments. For this project, FBG technology was used to measure horizontal strain and temperature at three elevations of the four external nave walls of St Mary Abchurch. This provided data at multiple points across the face and allowed monitoring of the development of building curvature during tunnelling. Another cable measured hoop strain of the painted dome in order to assess the influence of tunnelling works on this movement-sensitive heritage feature. Data was gathered from 80 sensors around the building every hour. FBG cables were also used to measure horizontal strains in the walls of the ballroom at Mansion House. In a first of a kind for CSIC, a single cable was used to measure both temperature and strain for external facades. The system has been live since July 2017 and has required minimal maintenance.

Advantages of fibre optics

Fibre optic (FO) sensing has been proven to be reliable, low-maintenance, and suitable for trigger alarm systems. It has a distinct advantage to traditional approaches for this application as it provides distributed strain measurements across the building, enough to ensure potential problems are identified in real time, and with relatively low cost and little visual impact. FO sensing measures damage directly via strain at a high enough resolution to avoid the assumptions typically required when inferring strain from sparse displacement data from traditional instrumentation, which can be unconservative. The fibre optic monitoring system installed at St Mary Abchurch allowed the project to take an informed observational approach and avoided traditional tunnel mitigation measures such as compensation grouting or temporary propping which would have been costly and disruptive (saving in excess of £1m).

3D Laser scanning

An innovative application of this technology has been employed to quantify existing damage in the buildings before tunnelling works by exploring distortions and rotations of the building facades with new algorithms. This is informing our estimations of the past settlement history of the building due to nearby excavations. Point clouds are also being used to measure deformations at the end of works, using techniques developed in earlier CSIC projects, to provide high quality deformation information on the facades and dome of the structure.

Training for Geocisa staff

CSIC provided training to the Geocisa survey team on how to use the fibre optic equipment hardware and software and familiarise them with the specific FO monitoring system of St Mary Abchurch and Mansion House so that sources of any problems could be identified quickly. Working together ensured effective maintenance of the system and the ability to identify anomalous readings.

Monitoring dashboard

Data from the FBG sensing was integrated into the monitoring dashboard system to complement the data from conventional sensors and has been used as part of the trigger alarm system. This is the first time fibre optic sensing data has been included in a monitoring dashboard for London Underground. It allows effective visualisation of the localisation of real-time strains, with digital 3D building models. This facilitates the communication of monitoring data to the construction teams and building owners.

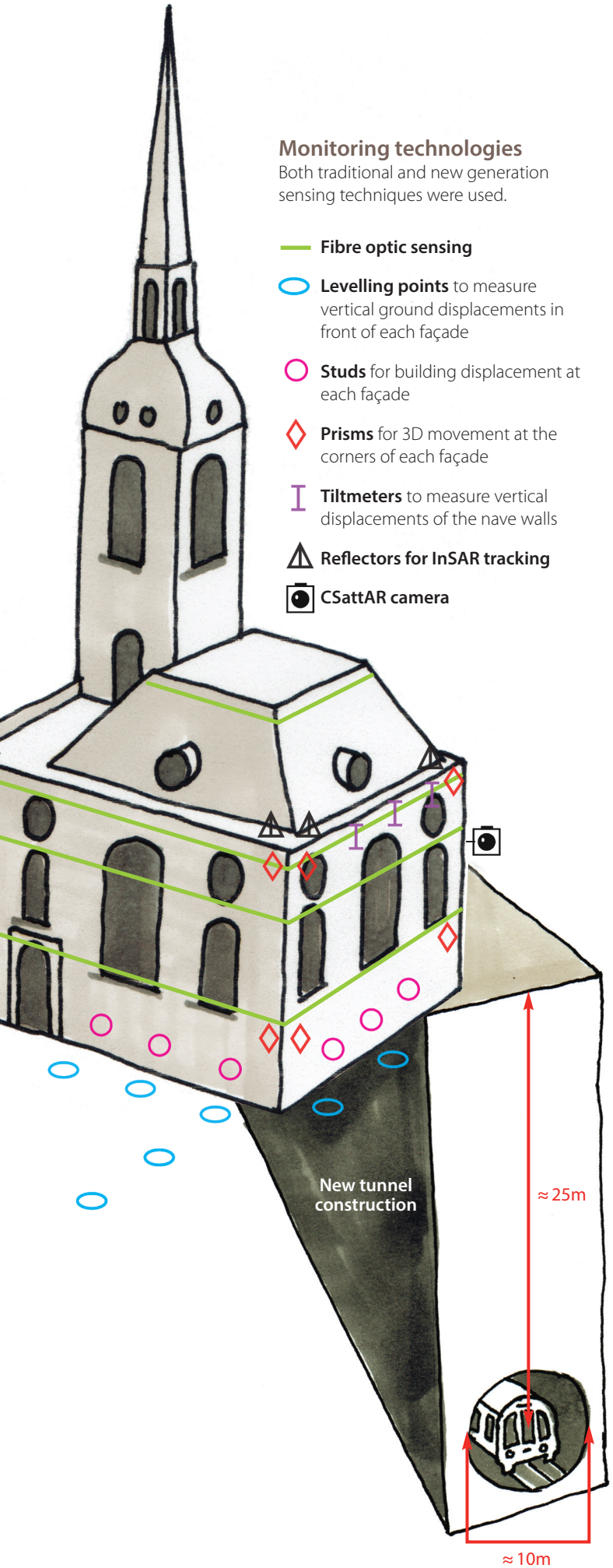
Understanding the response of the structures for future design: what the data and modelling revealed

- Advanced engineering assessments captured greenfield ground movements with remarkable accuracy. However, the building experienced higher strains than the greenfield. To find maximum strains it is necessary to model the building with its openings and existing damage.
- Inferred strains from measured displacements were significantly smaller than strains measured by fibre optics. This demonstrates the benefit of fibre optics to monitor building response during tunnelling.

Delivering value

This real-time monitoring project using state-of-the-art technology enabled savings in excess of £1m and led to an improved understanding of structural behaviour during tunnelling, which will enable further savings in future projects.

> "The innovative monitoring system used on Grade I listed buildings has provided the client with extremely informative and useful data. By adopting this system, we were able to feel comfortable that we would be first to know about any unusual response, and I hope the data collated will also provide valuable input to any future building damage assessments."
>
> Mark Dewhirst, Senior Project Engineer, London Underground



Relative displacement and strain deformation measurement using digital image correlation (DIC)

CSattAR, a photogrammetric monitoring system developed by former CSIC PhD student Mehdi Alhaddad which has proved successful in tunnel environments, has been used for monitoring the interior of St Mary Abchurch (including the painted dome) and the decorative plaster ceiling of Mansion House ballroom. Existing features in the painted dome and ceiling plaster were tracked by the low-cost, easily-installed CSattAR system which accurately measured real time relative deformations of structural elements at resolutions higher than 0.1 mm.

This CSattAR application is part of a larger project to provide a better understanding of the behaviour of the monitored assets when they are subjected to movements and also to validate and further explore the use of this new technology for monitoring purposes in varied environments and is funded by ARUP and CSIC. Contact: Dr Mehdi Alhaddad.

Relative displacement measurement using Interferometric Synthetic Aperture Radar (InSAR)

InSAR data from radar satellites are being compared with data from traditional measurement techniques at St Mary Abchurch and Mansion House to validate InSAR results and understand the opportunities and limitations of such measurements. The frequency and spatial resolution of satellite radar images has improved in recent years opening up the possibility of monitoring line of sight displacement as well as other phenomenon within infrastructure assets. However, the ability to identify specific monitoring points in densely developed areas such as the area around Bank Station is extremely challenging. In collaboration with the Satellite Applications Catapult with funding from Innovate UK, corner reflectors have been installed on St Mary Abchurch to allow the tracking of movement of very specific points on a structure and compare them with other monitoring data collected at the same points.

This work forms part of a larger University of Cambridge PhD research project investigating the advances in satellite measurement technologies to understand their relevance, utilisation, and limitations to civil engineering applications and is sponsored by the National Physical Laboratory with additional funding from Laing O'Rourke and support from the German Aerospace Centre (DLR). Contact: Sakthy Selvakumaran.

Benefit to

Heritage property asset owners, construction contractors, infrastructure designers

Impact and value

- real-time trigger assessments
- better understanding of the response of heritage structures to nearby tunnelling
- cost and time savings

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