

Monitoring Evolution

Newer monitoring technologies are coming of age, helping to increase our understanding of how existing infrastructure behaves and responds to tunnelling. Below TJ looks at a trial to embed wireless sensors into tunnel segments, how fibre optics are providing a more accurate picture of how ancient buildings respond to underground works, and look to Grand Paris Express where programme-wide satellite monitoring is promising new applications.

Embedded Wireless Sensors

The first stage of a pilot project to monitor precast concrete tunnel segments using embedded wireless sensors has been successfully completed on London's Northern Line Extension. The last 100m of one of the twin tunnels between Battersea and Kennington, constructed by JV contractor Ferrovial Agroman, Laing O'Rourke late last year, is now being continually monitored, courtesy of a system combining tilt meters and strain gauges, designed by wireless specialist Senceive.

For Neil Moss, head of practice, tunnels and major projects at Transport for London which is responsible for the underground network, the value of such monitoring regimes is less about the tunnel itself and more about what could appear around it. "Our aim is to design things that will last for a long time. We need to do very little maintenance on most things, particularly tunnel linings," says Moss. "The biggest risk is third-party risk, such as a developer who comes along and want to construct a building over the top of the tunnel."

"The problem that asset owners have is that they do not know what the current state of their infrastructure is in terms of insitu stress parameters," says Aidan Laimbeer, business development director at Senceive.

"So, when somebody wants to build another structure nearby, they don't know what percentage of their strain is already in the



structure to start with."

There are nine rings – one every 10m – with Senceive instruments embedded in them. At each ring, one segment contains a high precision triaxial tiltmeter and 4 strain gauges, the other segments have the tilt meters only. The position of the segment containing the strain gauges changes at each of the monitored rings.

"We wanted to measure strain in different segments in each ring, and with tilt meters in all segments we can calculate convergence," explains Senceive mechatronic design manager, Tom Drewett, who designed the embedded sensors especially for this application. As expected, some of the lower sensors were covered up when the track bed was cast, but they have provided data up to that point.

The wireless sensors are all battery powered with at least

12 years of life, and with no protruding aerial, there is no external encroachment into the tunnel envelope. The sensors are automatically connected to a standard Senceive 3G gateway to allow real-time data access from phone or laptop.

Senceive had an extremely short period of time to get its design from drawing board to pre-casting plant, Morgan Sindall's facility at Ridham. There were three months to develop the system and get the sensors cast into segments. Moss had been inspired to carry out the embedded sensor trial following a Senceive event last May where the firm had mocked up the idea of embedding sensors into track beds for long-term monitoring of railway lines.

The nodes – which are embedded with their upper face flush with the inner surface of the segment – are based on Senceive's existing wireless technology, with innovations for which Senceive is currently seeking IP (intellectual property) protection. But there were other aspects to consider such as selecting the right materials to cope with the temperature and chemistry of wet concrete, massive forces generated by the vibration process, and enclosing the antennae within the boxes.

"The most difficult part was that we came in quite close to the end of the casting period, so we could not modify the moulds in any significant way and we could not interrupt the casting process," says Drewett. Senceive came up with a cage to support the sensors within the mould; the segments were reinforced with steel fibres rather than rebar.

Despite the idea coming late in the day, there was good support for the trial, says Drewett: "The guys at the casting yard were pretty enthusiastic about it, and it had very little impact on the casting process."

For the TBM operatives, there was no difference in installation. Morgan Sindall stacked and supplied the segments in the right order, and the contractor installed them as normal.

The data travels from the sensors using Senceive's well-established FlatMesh technology which allows all the sensors or

nodes to talk to each other, with information travelling in the most efficient way to a 3G gateway. As the segments with sensors were first installed, the gateway was attached to the back of the TBM, and was collecting and storing the data immediately.

The next step for the Northern Line Extension trial will be to analyse the data coming out of the sensors to see what it can tell TfL about segment behaviour. In the meantime, Senceive is preparing for its next installation which it says will be on a different structure. With HS2 fast approaching, track beds most definitely remain an area of interest alongside tunnels.

Tiny total stations

Though they weren't used on this trial, Senceive is just launching a brand-new sensor which can measure distances, an optical displacement sensor (ODS).

"Up until now all our sensors have been localised and monitor what they are attached to," says Laimbeer. "With the optical displacement sensor we can take a measurement at the node from a distance of up to 150m away. It uses a laser system, the same technology and frequency as that used in automatic total station. The laser is integrated with a high precision tilt sensor inside one of our nodes." The advantages of this system over a total station are that they take up less space, they are quick to install, they are battery powered and are significantly

cheaper.

The ODS node, which has taken around a year to develop, can take readings continuously to any surface. "You can monitor displacement from the node and with the integrated tiltsensor, you are in the realms of picking up absolute movements from outside the zone of influence," says Laimbeer. "In a tunnel, you could work out whether there is convergence or divergence of the tunnel lining, automatically, wirelessly, twenty-four-seven to sub-millimetre precision."

One of Senceive's customers has been trialling the ODSs for three or four months on a variety of structures and has just purchased its first five instruments, with the intention of buying more. The instruments can achieve an accuracy of plus or minus 0.15mm which Laimbeer says is as good as, if not better than total stations. "It's a real game changer," he suggests.

Ancient buildings, new technologies

A novel monitoring project for two heritage buildings adjacent to extensive underground works for the £0.6bn Bank Station Capacity Upgrade in London is revealing new information about building behaviour and helping researchers to further develop monitoring techniques.

Working with specialist monitoring company Geocisa, contractor Dragados and client London Underground, the



Above: The sensors placed during the casting process

Cambridge Centre for Smart Infrastructure and Construction (CSIC) is deploying a brace of new technologies: fibre optic strain and temperature monitoring; CSattAR, a photogrammetric monitoring system; InSAR, a satellite-based monitoring technique; and a new application of 3D scanning.

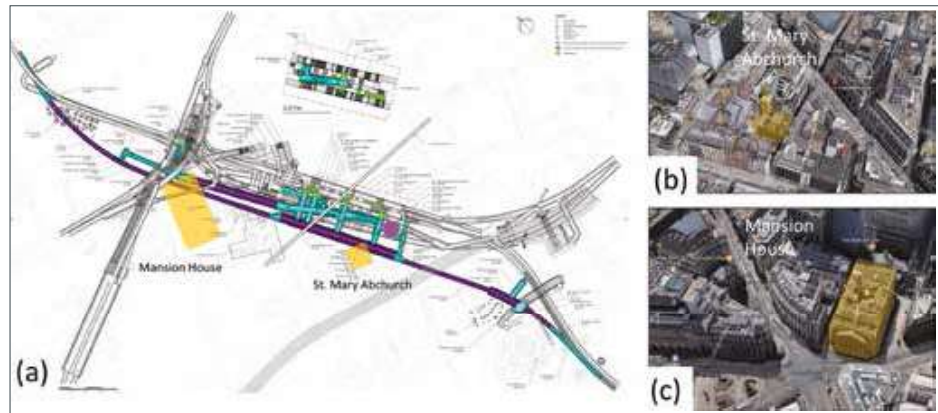
"Two of the buildings affected by the works are Grade I listed, and very important for the area," says Sinan Acikgoz, formerly a post-doctorate fellow at CSIC (funded by the Royal Commission of the Great Exhibition of 1851) and now an associate professor at Oxford University. "Although the assessment predicted that they would suffer negligible damage, it was still important to monitor them."

CSIC was contracted to provide fibre optic monitoring for St Mary Abchurch and The Mansion House. The church was designed by Sir Christopher Wren and built between 1681 and 1686, while The Mansion House was built between 1739 and 1752, and is the official residence of the Lord Mayor of London. Their Grade I listing denotes that they are buildings of exceptional historic and architectural importance.

CSIC is using a form of fibre optic sensing called Fibre Bragg Grating (FBG) static strain measurement, which is used in other industries, such as oil and gas, as well as underground for monitoring tunnels. Before CSIC could install the system in July 2017, it had to make adaptations for its use above ground.

"There was a period of development beforehand where we investigated techniques to improve the measurement accuracy and reliability of the sensing system," says Acikgoz. "We have been using similar sensing systems inside tunnels where temperature is more consistent. For our work on Bank Station Capacity Upgrade, we had to watch out for temperature and humidity effects and make sure the sensors could handle the environmental conditions."

CSIC came up with a new way of measuring and compensating for temperature effects. "The specific fibre optic cables we were using feature gratings along them. These gratings are areas

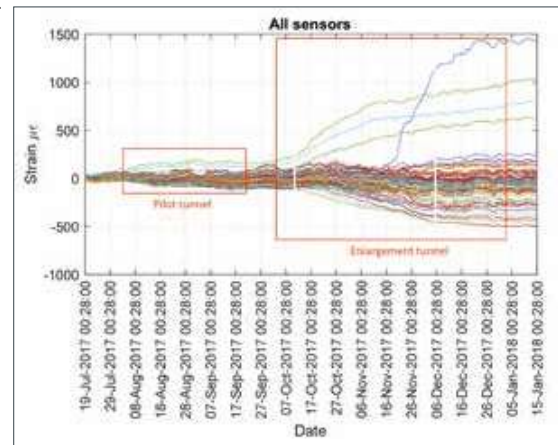


of different reflectivity. When you send a light pulse into the fibre, each grating - also referred to as a sensor - reflects the pulse at different wavelengths," explains Acikgoz. "This wavelength depends on temperature and strain experienced locally by the cable. We created a sensing system that would measure the temperature and automatically compensate for its influence on strain readings."

Researchers at CSIC also looked at a variety of coatings to help make the fragile glass core of the cable more resistant; they finally decided on a glass fibre reinforced polymer coating. They also had to work out how to attach the cables to these historic structures, leading to the design of unintrusive precision-engineered clamps which could be drilled into the mortar between bricks avoiding any damage to the building.

For the church there are three horizontal chains of sensors running around the building at three levels and one chain around its dome. "For this specially designed structure, the project didn't really have any other monitoring instruments available. Any significant readings from the fibre optics directed our inspections to specific areas," says Mark Dewhirst, senior project engineer with London Underground. In the Mansion House, the FBG system is monitoring the walls of its Ballroom.

The use of fibre optics has revealed new insight into behaviour. First, it has shown that the strains inside the buildings are slightly larger than the engineers initially predicted although the impact of works on the building were still negligible. Second, it has



quantified strains where they are hard to predict: above openings and in areas where cracks already existed due to past settlements and bomb damage during World War Two.

"To quantify the influence of ground movements in buildings, we typically measure building displacements, but to translate displacements into structural forces and predict damage, you need to know what the stiffness of the structure is," says Acikgoz. "This is difficult to determine ahead of time, and therefore there is a need to measure strains directly. The fibre optic sensing technology enables this."

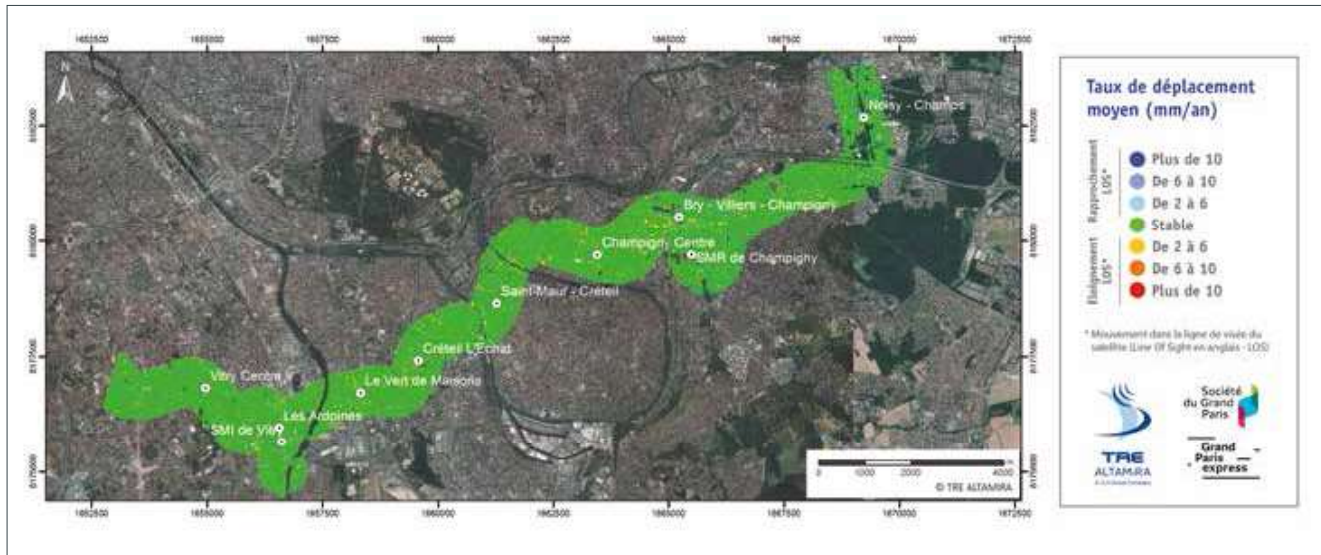
New technologies on trial

Also under trial on the two heritage buildings is CSattAR, a photogrammetric monitoring system developed by Mehdi Alhaddad, of CSIC and Arup. CSattAR is a digital image correlation method, comparing photographs taken at intervals, which has been successfully deployed underground, winning awards for its inventor.

"This is a technology with a

Top: (a) A scaled plan drawing of Bank Station Upgrade construction works with the new tunnels highlighted in magenta and cyan colours and relevant buildings in yellow. Reconstructed aerial images of two Grade-1 listed buildings affected by the tunnelling works, (b) St Mary Abchurch and (c) Mansion House, are also shown.

Strain monitoring data gathered from 80 sensors during the construction of the pilot and enlargement tunnels under St Mary Abchurch. The data enabled real time assessment of local damage around the building. The sensing system required minimal maintenance.



TRE ALTAMIRA used satellite images dating back to 2003 to map how the ground around the Grand Paris Express has moved over the years and alert client and contractor to any areas needing further investigation.

huge amount of potential," says Acikgoz. "It uses commercially available and inexpensive visible light cameras. CSIC previously used them in tunnels to look at how cast-iron segments move relative to one another. Using pixel tracking, movements smaller than 0.1mm can be detected in ideal conditions."

This trial looked to develop CSattAR algorithms for above-ground applications. At Bank, the camera was measuring displacements of the painted dome of the church and the coffered and plastered ceiling of the Mansion House Ballroom.

"Overground, there is a lot of natural light, which makes tracking patterns in images more difficult," says Acikgoz. "This project is developing better algorithms to track patterns in changing light conditions in order to achieve the required displacement measurement accuracy."

A second research project linked to the Bank Station job is using InSAR (Interferometric Synthetic Aperture Radar) to measure displacements of buildings in highly built-up areas, such as the City of London.

"Without needing to use artificial reflectors we could track millimetre-level displacements on building roofs using satellite data," says Acikgoz. "We have already processed some data which shows impressive results. We will investigate the reliability of this technology by comparing it to displacement data from more established techniques and

cross-comparing data from three different satellites, in different orbits."

The InSAR work is part of a bigger project, led by CSIC PhD student Sakthi Selvakumaran, sponsored by the National Physical Laboratory with funding from Laing O'Rourke, and support from Satellite Applications Catapult Centre and the German Aerospace Centre.

CSIC also used laser scanning to map existing damage to the buildings. "Laser scanning gives an idea of existing crack patterns and geometrical distortions in the building, which can be valuable input for building assessments" says Acikgoz.

Ongoing work is focussing on using this versatile data to measure displacements and look at movements. "We create 3D models from point clouds collected at different times, and use new algorithms to calculate displacements from these," says Acikgoz. "The displacement measurements of thousands of points around the building can be obtained in this manner."

Though Acikgoz does not think that these technologies will replace traditional ones in the near future, he sees them being used in tandem with traditional monitoring techniques to provide a greater understanding of what happens to existing structures when we tunnel underneath them, especially those of historical importance.

"The additional information we get about the behaviour of structures is valuable," says

Acikgoz. "We may be able to reduce the preventative measures, such as compensation grouting, and intrusive internal temporary works, or alternatively design thinner tunnel linings."

The use of these monitoring techniques can also provide greater assurance to the client, explains Dewhurst: "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 provide valuable input to any future building damage assessments. It is important that innovative monitoring methods be deployed as an effective risk mitigation measure and that any results can be used to inform decision making."

Programme-Wide INSAR Promises New Benefits

By the time the new Grand Paris Express metro lines are completed in 2030, client Société du Grand Paris (SGP) will have a record of ground movements along the route that stretches back nearly 40 years. SGP has contracted InSAR specialist TRE ALTAMIRA to use Interferometric Synthetic Aperture Radar (InSAR) to analyse retrospective ground movements and to monitor them as construction progresses.

It is an important project for InSAR technology, and not just because of its sheer size and duration. SGP is making the results of TRE ALTAMIRA's ground movement analyses available to all the companies involved in

the Grand Paris Express, from engineers to main contractors to specialist contractors.

"Société du Grand Paris took the strategic decision to provide this information to everyone as a service," explains Anne Urdiroz, sales manager for TRE ALTAMIRA, who has been closely involved with setting up the monitoring project. "This is the first time a client has taken this approach and the challenge for us was to make the information available in a way that was fast and understandable. People have so many other things to think about, they don't have time to learn about a new service."

The solution was a simple web-based interface that users can access from a smart phone, tablet or PC. Ground movements are colour-coded: green for no movement, red for subsidence, blue for heave.

Though construction has only recently begun on the southern section of Line 15 – one of four planned new lines – there are already over 100 users on the system, each with the appropriate level of access which allows them to see the information relevant to them.

At first, says Urdiroz, people can be unsure of the value of the InSAR data. But once they see the correlation between it and more traditional surveying methods, they start to see its potential. The historic InSAR data has already proved useful for engineers and contractors on Line 15 in relation to identifying risks due to ground conditions and movement of older buildings.

"We see that slowly, as the work progresses, people are starting to work with the tools, checking the area and looking at the temporal resolution," says TRE ALTAMIRA project manager Fifamé Koudogbo.

Looking back

TRE ALTAMIRA began work on Grand Paris Express in March 2015. Its first task was to use existing satellite images to assess ground movement in a 1km-wide corridor along the 200km route. InSAR measures the distance from the satellite to points on the ground, so by comparing successive images, experts can calculate ground movements.

TRE ALTAMIRA has developed an algorithm, which it calls SqueeSAR, that allows it to process any satellite imagery and to achieve an accuracy of around 1mm per year. In the case of Grand Paris, TRE ALTAMIRA used satellite images from European Space Agency satellites for the years between 1992 and 2010, moving to higher-resolution satellites belonging respectively to the Italian and German space agencies from 2011 onwards.

That initial historic analysis took place in just three months, which was a tight schedule, says Koudogbo. "Even for us, it was a huge piece of work," she says. "To do a complete study for 200km and to separate out the different contracts, it was a short timeframe."

TRE ALTAMIRA combines the history and experience of two InSAR companies, TRE Europa and Altamira Information, which were both acquired by global specialist CLS Group. With offices in Barcelona and Milan – as well as Vancouver – TRE ALTAMIRA employs around 72 people, over half of which are interferometry specialists with background in telecommunication, radar techniques or remote sensing.

Now that construction is underway on the Line 15, TRE ALTAMIRA is using images from the German Space Agency's TerraSAR-X satellite for this section of the works. The satellite can measure over 10,000 points per square kilometre and gives measurements which are accurate to within 1mm per year, updating its image every 11 days.

Koudogbo and her team provide a monthly report on ground movements as well as training sessions for any of the users once every two or three months. In between monthly reports, Koudogbo keeps a close eye on the analyses. "This is such an interesting project to be involved with," says Koudogbo. "When I look at the results, if I notice anything unusual, I call the relevant engineer to see if the areas are of interest to them."

Old and new combine

The historic InSAR analysis has already come in useful on parts of Line 15. Setec, which is designer

and construction manager for the western section, has used the data to identify areas of risk due to ancient underground limestone quarries and has verified its application for the monitoring of building movements.

TRE ALTAMIRA's historic mapping flagged up areas of movement close to the Line 15 tunnel route. One area showed significant settlement, with analysis of ground movements over time suggesting that the ground may still not be stable.

Areas such as this will require further investigation and possibly treatment, such as backfilling, before the TBMs pass through. Ongoing satellite monitoring will show the impact of such treatments, supplementing conventional surveying techniques.

“We are just at the beginning now. Over time many people in the industry will find ways to use this information for improving the safety of works.”

Anne Urdiroz, Sales Manager for TRE ALTAMIRA,

During the preliminary phases of the Grand Paris project, injection grouting beneath buildings took place to prepare for the tunnelling works. The movement of a 1930s masonry building near to the tunnel's route was monitored by Gauss Monitoring using total stations and prisms and the results compared to those acquired through InSAR.

The results correlated well. The InSAR data – because it stretches far beyond the zone of influence for the tunnel – can also be used to check the reference points used for traditional surveying techniques.

As the project progresses, TRE ALTAMIRA believes that the InSAR data will prove useful for spotting trends and for forensic analysis. "We are just at the beginning now," says Urdiroz. "Over time many people in the industry will find ways to use this information for improving the safety of works." 