



Wireless remote condition monitoring for more efficient
tunnel construction and operation



Markus Rennan & Simon Brightwell
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EVERY TUNNEL IS EFFECTIVELY A PROTOTYPE

Tunnel engineers responsible for construction or maintenance face challenges not found in other areas of civil engineering. The variability of subterranean conditions and the complexity of interaction with other infrastructure mean that every tunnel is effectively a prototype. Today's tunnellers cannot simply over-design and accept the occasional failure like their predecessors may have done a century ago. Clients want decisions to be data-driven and expect to have early warning of even subtle changes in conditions in order to safeguard the integrity of their structures, third-party assets and the wellbeing of people. While the instrumentation and monitoring industry has proved highly inventive in providing sensors that can measure a wide variety of physical, geospatial, and environmental parameters, challenges have remained in deploying them effectively underground.

Common challenges include:

- No mains or solar power
- No satellite or cellular coverage
- Highly restricted access
- Distance from portal/surface
- The constraints on physical space, particularly near the tunnelling face where most movement occurs
- Aggressive conditions that can include excessive heat, moisture, vibration, humidity, acidity/alkalinity, dust and combustible gases

Widely used monitoring technologies range from manual methods such as visual inspections and tape extensometers, to methods using automated total stations, laser scanners and photogrammetry. Each provides valuable information, but none truly address the challenges listed above, with drawbacks including the need for frequent access, power supply, cabling and cost.

One of the key developments that has helped the sector address these challenges is the application of wireless remote condition monitoring platforms. These enable the integration of a multitude of sensor types and the transmission of the derived data to a user who may be located anywhere in the world.

While hardware cost may be higher than traditional survey methods, the cost of ongoing operation is relatively low due to the simple installation and virtually no need for onsite manpower or access support. Unlike optical systems such as automated total stations, there is no need for frequent cleaning of prisms; sensor nodes are small enough to be fitted where needed without compromising clearances, and batteries will not require replacement for 10 to 15 years, assuming 20 to 30-minute reporting intervals.

Typical sensor nodes and parameters measured in a tunnel.



WIRELESS SETUP

A wireless remote condition-monitoring system typically comprises three elements:

1. Sensor nodes

Sensor nodes measure a range of parameters, the most widely used being high-precision tilt sensors which measure tunnel rotation about the horizontal axis. With the use of triaxial sensors the instrument can be commissioned at any orientation on any surface. Other widely-used sensors are crack/displacement gauges, optical displacement sensors and a family of vibrating wire-based devices including piezometers, strain gauges, load and pressure cells, not to forget in place inclinometers, temperature and moisture sensors.

2. Wireless communication platform (WCP)

A WCP collates information from the various sensors, then transmits the data to a gateway/monitoring hub from where it is relayed to the internet or directly to a client's private network. Most tunnel applications use a mesh platform such as Senceive's Flatmesh™ in which nodes 'talk' to their neighbours, relaying data in a series of hops to the outside world.

Solar-powered gateway transmitting data from a wireless monitoring system in a Spanish tunnel.



This dynamic, non-hierarchical system is extremely robust and can tolerate damage to individual nodes without systematic loss of performance. It is suited to dense networks concentrated in relatively small areas. Where deployment is needed over greater distance (kilometres) a lower frequency LoRaWAN radio platform can be used. This family of technologies has the power to transmit through physical obstructions enabling, for example, integration of sensors in boreholes or on buildings above the tunnel with movement sensors measuring deformation inside the tunnel. From the gateway or monitoring hub the options for getting the data to the outside world are restricted only by the available infrastructure. The simplest option may be the cellular network; alternatively, Wi-Fi or ethernet may be used.

3. User portal

This enables viewing and interaction with the monitoring output. Most remote monitoring setups offer a bespoke viewing tool and a choice of data delivery formats that are compatible with industry standard management software such as Leica GeoMoS Trimble 4D Control, Topcon Delta Watch, Mission OS, Geoscope, Eagle.io, Calyx OMS and many more. Varying degrees of remote interaction are possible. Flatmesh users can change configuration settings such as sampling frequency without site visits - this constitutes a significant safety and cost benefit where tunnel access is constrained.

SITE CONSIDERATIONS

While sensor nodes have a battery life of many years, the gateway that transmits data to the client requires a power supply. The most straightforward option is to use mains power where available. Alternatively, it is often possible to position the gateway outside the tunnel powered by a solar panel. Where tunnel length prohibits this approach batteries may be used, but these will require periodic replacement.

Measurement of tilt at any specific point may yield limited information due to the very small displacements involved and in the case of masonry structures this will be representative of a single brick or block rather than the wider structure. To provide a more representative picture, tilt sensors can be mounted on a beam bolted to the tunnel wall to measure movement between the two anchor points. Further insight is gained where several beams are connected to form a string. In this way, the method provides a viable means of measuring heave or longitudinal settlement, with a 50m-long string having a typical repeatability of around $\pm 0.5\text{mm}$.

Ease of use is a key advantage for modern wireless monitoring tools. In the simplest cases, installation can be undertaken by the contractor, engineer or surveyor already working on the site. The experience of a specialist contractor will often be called upon for more complex deployments, especially for reporting and interpretation. With nodes brought to site already operating and ready to go, they can be installed with brackets simply bolted, glued or magnetically fixed to the tunnel lining. Where triaxial sensors are used they can be fixed at any point around a tunnel arch. Deployment can be highly efficient in terms of optimising short access windows: one person would typically fit a tilt node to an arch in under ten minutes or to a track sleeper in few minutes. A further advantage is the small size and robust nature of the sensors, which means they can be fitted very close to the cutting face without being snagged by a TBM or associated utilities.

PROJECTS

An early demonstration of the value of wireless remote monitoring was London Underground's 2009 Bakerloo Line repair project. A section of bolted cast iron segmental lining had deteriorated and required replacement with new segments and grout injection behind the lining. The works were compressed into short overnight access periods with the track handed back for service each day. Understanding the impact of such an intrusive process on the tunnel profile and integrity was crucial, particularly in view of the time pressures. Wireless tilt meters were used during the highly congested work zone. Thanks to their small size and lack of cables, they were able to deliver movement data without being damaged, nor did they disrupt construction works. With magnetic fixings, the nodes were simply moved along the tunnel as the works advanced. Since then, the technology has been used in more than 100 tunnelling projects around the world and installed for longer-term structural health monitoring purposes. Typical applications include new and existing tunnels, shafts, stations and underground mine tunnels.

A recent project in Spain involved the large-scale use of optical displacement sensors to monitor deformation of a series of old masonry tunnels being converted for modern high-speed rail use. Modifications including sprayed concrete lining and track lowering meant there was a need to understand convergence and divergence. Challenging site conditions led to the rejection of conventional monitoring methods. The use of automated total stations was ruled out because construction plant and temporary props would obscure line of site, while very dusty conditions would obscure prisms without frequent cleaning. Lack of a power supply further complicated matters. In this case, a long range wireless system was chosen because it had the power to relay data from the sensor locations to a solar-powered gateway at the tunnel portal with an internet connection. As well as measuring movement at points across the tunnel, longitudinal movement was also being monitored using a series of tilt nodes mounted on steel beams fixed to the tunnel sidewalls. Borehole inclinometers measuring settlement above the tunnel were fully integrated into the system.

Tilt node checking for movement on the first ring during construction: note proximity of the TBM ram.




The growing demand for long-term structural health assessment is likely to see more asset owners opting for wireless remote-condition monitoring technology. A recent project in the Netherlands, the Botlek Tunnel near Rotterdam, provides a good example. Dutch monitoring specialist IV Infra installed a Senceive system shortly after construction of the 1.8km concrete segment-lined rail tunnel.

Challenging site conditions resulted in the tunnel owner setting a demanding specification for the monitoring programme: the system was required to operate in near real-time and measure the angle of lining movement at a repeatability of $\pm 0.0005^\circ$. It also had to be easy to install, fully automatic, as well as discreet, extremely reliable and able to operate for 25 years. No mobile signal or internet access was available and site visits for maintenance had to be kept to the bare minimum to prevent disruption to the railway.

The implemented solution was based on Senceive's FlatMesh™ comms platform, with 434 tilt sensors deployed in rings around the tunnel at 30m intervals. The 25-year life could be achieved with a single battery change and configuration changes could be made remotely.

INNOVATION


As with other internet-of-things (IOT) technologies, a key element is system automation. Mark Ferris, chief technology officer at Senceive explains: "Our systems can be configured to change their behaviour in response to events. For example, if a tilt sensor detects movement, it can automatically increase its sampling frequency and that of its neighbouring tilt meters to build a more reliable dataset; or 'wake up' a camera which can send a high-resolution image of the location to stakeholders." The same process can, for example, include automated transmission of alerts to nominated stakeholders.



Tilt node installed on a beam to monitor horizontal movement; above it, an optical displacement sensor measuring sidewall

Another smart move made possible by the availability of miniature nodes with ultra-long lifespans is the ability to embed sensors into concrete segments. This proved effective on London Underground's Northern Line Extension project where strain gauges were cast into the concrete and data recorded alongside a tilt sensor inside a preformed enclosed recess in the precast segments so that the profile of the intrados was unchanged. This formed a lining that could effectively monitor itself for the lifetime of the structure and represents a small step along the journey towards truly intelligent infrastructure and whole-life structural monitoring.

Another evolving area is the incorporation of near field communication (NFC) – the technology behind contactless payments. Using a mobile phone app, this enables users to make quick and simple changes to sensors with just a tap. It is quite simple, for example, to change the mode of a node from being active to being dormant in order to extend its battery life during storage or transit.



Nano Tilt Sensor monitoring deformation of a tunnel

CONCLUSION

Wireless remote condition monitoring provides asset owners with a new level of reassurance and helps them address a raft of topical challenges. The monitoring systems enable data-driven decision making and are ideal for whole-life structural health monitoring. Reduced need for site visits through ultra-long battery life and the ability to change settings remotely cuts the need for potentially risky site visits. Systems equipped with solar-powered gateways outside the tunnel further enhance green credentials.

It is perhaps no surprise that industry experts predict significant growth in global adoption of wireless monitoring technology.



Nodes attached at various positions on the tunnel surface

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info@senceive.com