On the Move

The Future of underground monitoring is integrated, data-driven, and customised, reports Desiree Willis

Above: Real-time vibration monitoring was an MTRC requirement in the Admiralty tunnel for the Sha Tin Central Link Expansion.

With the rapid pace of change in today's world, monitoring is more imperative than ever. From climate change - resulting in leading insurers requiring flood monitoring for the first time - to integration with AI and BIM, monitoring is integral, customizable and data-driven. The trends are poised to only increase, as monitoring becomes part of an overall program to interpret and manage risk, analyze cause and effect, and more.

From AI to BIM and Beyond

AI has risen to prominence in a big way, with the potential to play a critical role in predictive monitoring and other capabilities. It's a development that Klaus Rabensteiner, Managing Director for Austria-based Geodata sees as promising. "AI algorithms can analyse historical data to identify patterns and trends that might lead to potential issues. AI can help identify correlations between different data sources, and potential causes of certain behavior, aiding engineers in getting insight and making informed decisions. However, the complex nature of tunnelling processes involves multiple variables and interactions, making it challenging to create accurate, predictive models, and for the time being it is certainly impossible to replace skilled tunnel engineers."

Geodata has been investigating AI for the past five years, with feasibility studies and research prototypes for processing monitoring data by different AI/Machine Learning (ML) methods and for different purposes like deformation pattern detection, geotechnical interpretation, or prediction. "AI's effectiveness relies heavily on the quality and availability of data. Incomplete, biased, or inaccurate data lead to unreliable AI predictions and false alarms," continued Rabensteiner.

One way Geodata is working to ensure more reliable and accurate AI results is through participation in the cybersecurity-focused EUREKA research project CISSAN. The goal is to develop AI-based technologies to assess the quality of monitoring data, detecting errors, inconsistencies, and outliers. Geodata hopes to incorporate the technology into their monitoring platform GeodataHub KRONOS soon.

At global monitoring data specialists Maxwell Geosystems, Director Angus Maxwell is also analysing the challenging aspects of AI: "Historically, most applications have been focused on creating autonomous machines, which automatically adjust driving parameters based on observation of other machine sensors. This is essentially using the machine as a sensor as well as a mining tool akin to a self-driving car."

While machine learning is the extension of this, continues Maxwell, it's not an easy next step. Operators typically still rely on a geotechnical prediction made at the start of tunnelling—a data set that often is not updated. "TBMs do not currently have the monitoring capabilities to make informed, predictive decisions based on the ground ahead. Through our recent use of "data-driven" geostatistical models we have been able to provide the TBM and operators with a gridded numeric representation of the ground for a variety of important parameters. Each has a measure of the level of confidence highlighting current geotechnical risk." Maxwell Geosystems are working to design feedback systems into their software platform, MissionOS, to recalibrate predictions based on observations and offer operators advisories with the potential to optimise tunnel processes.

Building Information Modeling (BIM) is another technology seeing an upward trend, but more standardisation is needed. "It is more about the integration of monitoring data into the context of construction and this means the ground model, the design including the temporary works, the progress and activities and the information about the impacted environment surrounding the works," said Maxwell.

There is a need for more connection between the data collected for BIM and development of methodologies specific to tunneling as well. Work is underway to create a set of guidelines and standards specific to tunnelling, as both Rabensteiner and Maxwell are part of the ITA Working Group 22 on Information Modelling in Tunnelling. "In the near future, we will see more and more monitoring software offering some BIM compatibility on the data level, meaning that exporting/importing monitoring data following BIM standards like Internet Foundation Classes (IFC)-Tunnel will be possible. This will happen as soon as BIM standards are available and become obligatory for monitoring data, which is not yet the case," said Rabensteiner.

Data Advances

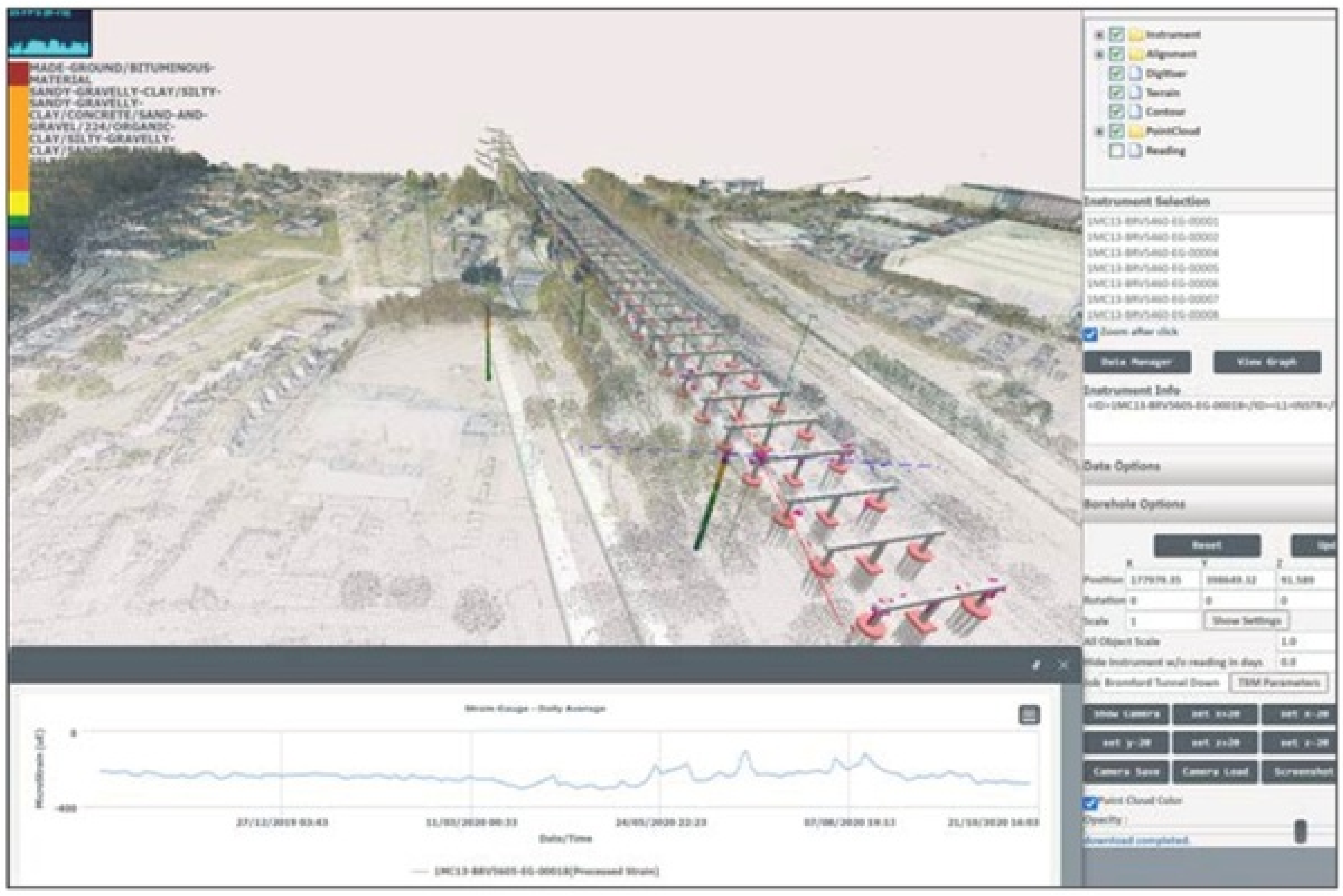
The flow of data has undergone its own evolution. For many years all transfer was by file, and software absorbing those files had to wait for the files to appear and make do with whatever appeared. "There has been a shift towards cloud-based solutions for data management, visualisation, and analysis that offers scalability, accessibility, and collaboration advantages over traditional local software installations," said Rabensteiner. "Better connectivity and the anticipation of 5G/6G networks enables real-time monitoring applications and the efficient transfer of large data volumes within short timeframes."

Direct connection with gateways and loggers makes the information accessible directly from the web. "Management software can now provide Application Programming Interfaces (APIs). This enables our systems to communicate to the systems of data producers and "talk" about what data we want, how it should be given and when," said Maxwell. The APIs reduce the data transfer time and give the added benefit of passing QA/QC information on the data to avoid false alarms. "In some cases, we can implement bidirectional control where we can tell the control software to implement a change in its mode of operation based on other data we may be recording." That bidirectional control can be done via two-way internet messaging (MQTT) for minimal information delay.

Bidirectional communication can also be done machine to machine, a system that Maxwell Geosystems set up on the HS2 project in the UK. The number of instruments on the project exceeds 1 billion, and with so much data they have implemented blogging methods to manage any events. "The faster you can get that information, the faster you can manage any mitigation needed. Blogging allows them to document things happening live and in real time. It's been very effective."

Pulling in Ideas from Industry

Monitoring hardware itself is evolving rapidly – taking a cue from unlikely industries. At Hong Kong-based Global Sensing Solutions (GSS), that industry was sports science. In the mid-2010s co-founder Steve Sparrow was offering sensors for use in golf clubs to track swing profile and ball tracking, as well as in bowling balls and cricket bats. Maxwell approached them about using some of that same technology to design an accelerometer array at a new ocean terminal in Hong Kong. From there, GSS was founded in 2014 to specialize in wireless sensor infrastructure, both above and below ground. "All the features we had developed – small, wireless, low power—were features we realised were missing from the tunnelling market," said GSS COO Darrin Couch. In addition to



A digital twin view in MissionOS, showing HS2 near Birmingham adjacent to a viaduct for the key road artery to the NW of England.

The GSS wireless sensors in the MTR tunnel at Admiralty featured remote management and monitoring capabilities.

the use of accelerometers to monitor vibration, the company expanded its concepts to tilt monitoring. "Accelerometers are great for fast movement, like vibration, but not slow movement over a long time required for deformation. However, high-precision accelerometers are great at measuring tilt, and when using many in a line they can be used to accurately calculate deformation through the use of trigonometry."

The company's latest wireless sensor can switch modes to monitor either vibration or tilt, all within the same housing. For example, a given monitor could be in vibration mode during the day when construction is happening and switched to tilt mode at night, to monitor tilting of the surface on which it is mounted.

The monitors are all modular and highly customisable, and it's a direction that Couch sees as beneficial for the industry. "It's a benefit for many reasons, including speed to market. It doesn't take as long to produce something new because the products build on each other. I can customise monitoring for a project in a very short period of time because at their core, the base hardware, firmware libraries, and gateway functions are all the same. It's also a benefit to the client – once they know how to

At Geodata, a product where optical fibres are embedded in measuring anchors has been developed to inform about their load development and status.

configure one device, they can configure the others."

The modularity also carries through to each sensor's connectors. One connector is a USB used for serial communications and external power. The other side is an auxiliary port that serves as a gateway for modular devices that support cabled devices, such as vibrating wire piezometers, strain gauges, or sound meters. The sensor itself serves as the gateway, transferring data through mobile 3G/4G/LTE, Wi-Fi, Bluetooth or other pathways depending on what is available at the site and the client preference. "All of the processing is done within the sensor. We are not sending data to a backend system to calculate engineering units – all calculations occur within the sensor, which is how we are able to send alert messages and data files within seconds via SMS or MQTT to a phone or backend system," said Couch.

Project requirements are pushing the limits of wireless monitoring devices even further: to near-real time. GSS is working on a new system for a tunnel in Hong Kong, designing high-precision tilt sensors that can provide data within one (1) arc-second, a common ask for total stations. "Monitoring total stations are great, but this tunnel is quite long and windy. Total stations require line of sight, so this would be quite expensive to do. They needed another way to monitor deformation," said Couch. The company is using (1) arc-second tilt sensors on segments along the tunnel and mathematical computations to calculate deformation.

Lifetime Monitoring

Monitoring setups that can last for the lifetime of a tunnel remain a goal of the industry. Embedded monitoring using fibre optics within tunnel segments can be useful in some circumstances. "Long-term monitoring is an issue, and embedded fibre optic cables promise to allow for decades of uninterrupted and maintenance-free strain monitoring," said Rabensteiner. "In some conventional tunnelling projects, fibres have also been embedded in the shotcrete layer during construction. At Geodata, most recently, we have developed a product where optical fibres are embedded in measuring anchors informing about their load development and status."

Other examples also exist - Singapore's Deep Tunnel Sewerage System (DTSS) Phase 2 is currently installing optic fibre along the whole of its composite secondary lining, which they will monitor for structural health and deterioration under the aggressive sewerage conditions. "For these large applications the high cost of the signal analysers can be absorbed but unfortunately not for small applications," said Maxwell. Use of fibre optics, particularly in tunnels shorter than 25km in length, he says, is still largely driven by research. "Once the cost benefit is established, we hope to see more application of these techniques since the data coverage is a step beyond where we currently are."

In a well-publicised application of the first embedded wireless sensor for segment monitoring, a bespoke solution was developed for Hong Kong's Liantang Lung Shan highway tunnels with GSS involvement. "We designed strain gauge modules that could be embedded inside concrete and talk to other strain gauges. Everything went back to a data logger that was accessible by Bluetooth. The sensors showed that when comparing steel reinforced rebar segments and steel reinforced fibre, the fibre performed better. Not only that but it was also more cost effective," said Couch. The project was reported on in the June/July 2018 issue of Tunnelling Journal, "Monitoring Evolution".

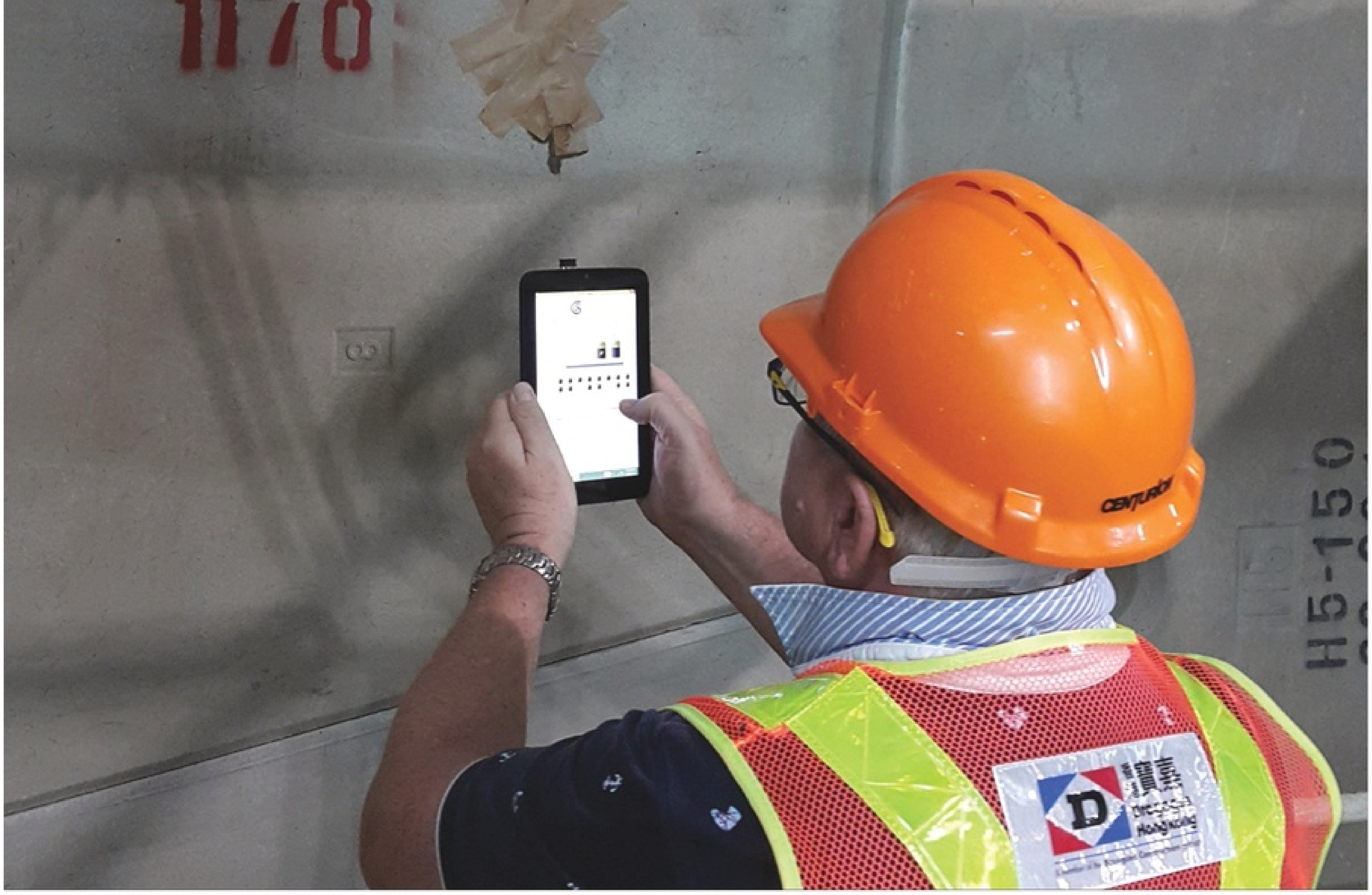
Geodata are continuing the trend with their use of distributed fibre optic strain sensors in segmental lining for long-term monitoring at the Semmering and Brenner base tunnels. "We also did some drone-based deformation monitoring and installed fibre optical measuring anchors in tunnels of the Austrian tunnel research facility Zentrum am Berg," said Rabensteiner.

Tunnel scanning is another development on the rise, which can provide valuable information on the status of a completed tunnel structure from the shotcrete to segments to cast in place linings. "It's nondestructive, and it's easy to do. We are doing it on tunnels to compare the as-built structure with the design," said Maxwell.

What's Next

Changes in contracting models worldwide, says Maxwell, are making waves in the world of monitoring. Alliancing and Public Private Partnerships (PPP) are being reconsidered in many areas, with risk management a key focus for all parties. "With most projects historically being lump sum design and construct there has been little focus on value engineering monitoring except to get the lowest price for the minimum scope. With movement toward target costs contracting, especially with early contractor involvement (ECI), and value engineering clauses, there is an opportunity to really use monitoring as a tool to manage uncertainty and open up and de-risk alternatives to the initial reference design."

Those changes in the view of risk have opened up more integrated monitoring solutions than ever before. At a large international project, Maxwell Geosystems is providing a total tunnel construction



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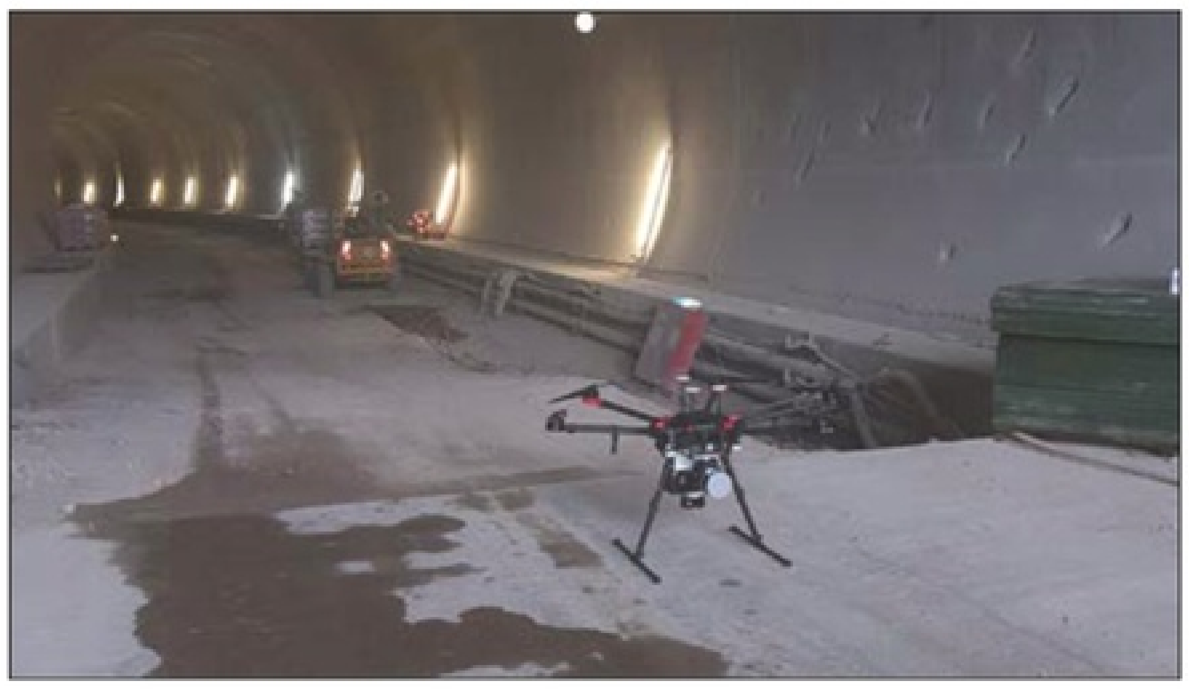

Tunnel mapping via drone can be used to create 3D models with potential applications for enhanced visualization such as augmented or virtual reality.

data management system covering all aspects of tunnelling—from probing and mapping to drilling and production. "We can relate everything together. For example, if groundwater is coming in during probe drilling through the face, we can see if anything is moving, and look at causes and effects."

The systems utilise geostatistical modelling – creating a stochastic model of the ground to represent the collected data, determine the possibilities and interpret the overall level of risk. The move towards geostatistical modelling is in part driven by insurance companies, says Maxwell, and by contractor demand. "It's about all aspects of tunnelling such as cutter wear potential, as well as geological aspects like particle size distribution. The data generated could also serve as a digital input for machine learning and AI," said Maxwell.

The trend towards ever increasing amounts of data is also seen by Geodata. There is a clear move toward having all construction phases fully documented in 3D by scanners or photogrammetric systems, says Rabensteiner, for geological documentation and proof of the excavated profile concerning over- or under excavation. The 3D documentation has other applications as well: "Extended Reality (XR) technologies like Virtual Reality (VR), Mixed Reality (MR), and Augmented Reality (AR) are being implemented slowly, but there is great potential for enhanced data visualisation, enabling immersive experiences that can aid in understanding complex monitoring data."

The vast amounts of data captured by 3D documentation and geostatistical modelling—not to mention more standard monitoring programs—brings another issue to the fore: What to do with all the data? As large tunnel projects generate terabytes of information, is there a responsibility to preserve and share that data with future generations? Whether archived by university programs or as part of international guidelines and standards, there is much to learn and apply on future tunnelling projects. The immense wealth of information the industry is generating is sure to make the future of underground monitoring a bright one.