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Monitoring of rock mass movement using a distributed array of wi-fi enabled extensometers

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Abstract

Measurement of ground movement into the rock mass around underground openings enables quantification of the timing, failure mode and depth of rock failure. Geotechnical instrumentation, such as extensometers, help to evaluate the performance of the ground support system, which leads to improved ground support design. The use of extensometers that monitor rock mass movement into and around the excavation are seen as complementary technology to LiDAR and other convergence monitoring.

This paper outlines the development of an Internet of Things platform that comprises a four-anchor wire extensometer with integrated data logging that is wi-fi enabled. The system is supported by an analytical software suite.

A case history provided from Fosterville Gold Mine outlines the deployment of RockSHIELD® in a wi-fi denied environment (tablet-based) as well as a fully networked, surface-controlled distributed array of sensors operating on a web-based platform. Integration with tablet- and web-based software enables operational personnel to readily access the data and manage ground fall risk on a shift-by-shift basis.

Discussion is provided on the integration and synergies with LiDAR and other ground convergence monitoring approaches to fully utilise the value of current ground monitoring systems.

Keywords: *extensometer, wi-fi, ground support, rock mass monitoring, Fosterville Gold Mine*

1 Introduction

Monitoring of rock mass movements in underground excavations is an intrinsic part of the rock mechanics design process. In various mining jurisdictions in Australia (including Western Australia, New South Wales, Queensland and Victoria), state-based legislation provides for ground control risk management using trigger action response plans (TARPs) coupled with rock mass monitoring (Department of Mines, Industry Regulation and Safety 2019).

Rock mass monitoring can take many forms depending on a range of factors including (but not limited to) excavation use, excavation and support methodology, excavation size, rock mass conditions and associated ground response, cost, time, available technology and risk profile.

SCT Operations (SCT) has, for many years, utilised simple two- and four-anchor multi-point mechanical borehole extensometers (Rock-IT) as part of the routine monitoring of mining tunnels. The analogue Rock-IT (Figure 1) is used for monitoring rock mass movements associated with traditional short (2–3 m) and long (6–10 m) support elements and providing a real-time visual reading to mining personnel. Mechanical extensometers provide a reliable and accurate measurement, however, they rely on mine personnel to monitor and record data, and 'keeping track of the measurement from these devices is an enormous workload because of the large number of units deployed' (Vallati et al. 2020).

The more recent and ongoing deployment of wi-fi (and other) mine-wide communication frameworks has provided the opportunity and stimulus to digitise both the hardware and associated software data interface.

This paper outlines the development of RockSHIELD®, an Internet of Things (IoT) based system that comprises a simple four-anchor wire extensometer digitised to be a smart telltale (SmartTT) with integrated sensors and logging to a wi-fi head unit and associated tablet and PC software suite.

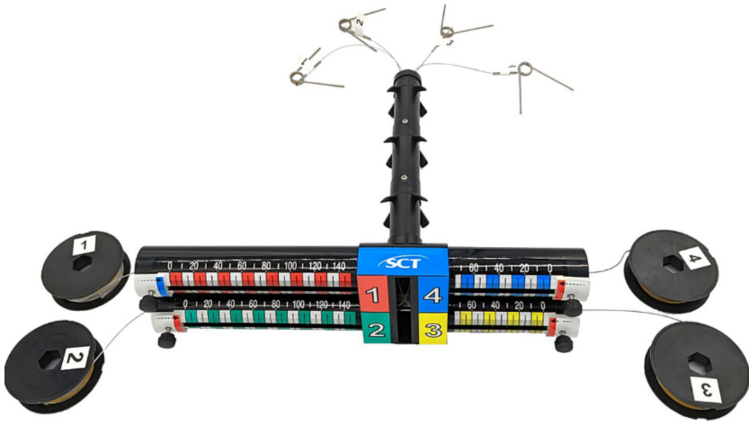

Figure 1 Analogue four-anchor multi-point extensometer – Rock-IT

2 Design brief

Building upon our experience developing and using analogue instruments, the approach has been to provide a cost-effective IoT integration of ground monitoring data. While initial development has focused on the digitisation of four-anchor Rock-ITs, we are also in the process of integrating tiltmeters based on micro-mechanical sensors based shear sensors and strain gauge-based rock and ground support monitoring.

In this sense, the design brief is to provide for a broader array of integrated sensors measuring rock mass and ground support response.

Key inclusions for the RockSHIELD system include:

- Simple and proven multi-point borehole extensometer uphole assembly that requires no grouting and is quick to install.
- Wi-fi connectivity to a range of common frequencies and the ability to log and store data when not communicating.
- The ability to operate where no network wi-fi exists by using a tablet in local mode to communicate and download data (through local wi-fi connection directly).
- Installation that requires no specialist trades (such as electricians) – plug and play connectivity.
- A scalable distributed array of sensors on the network and software interface.
- Tablet and desktop (web) software user interface.
- Standalone data logging capability.
- Removable and rechargeable battery module.
- Reusable and upgradeable (firmware) head units and battery packs.
- Integration of live data with a range of third party software applications – including mXrap.

The use of wi-fi instrumentation provides several challenges including the deployment and maintenance of large wi-fi networks. Like most industries, underground mining has seen an ongoing trend of automation and integration. In this sense, the use of wi-fi (and other) networks underground to monitor and manage the underground environment is becoming increasingly common.

A key design challenge for wi-fi instruments is energy use and, ultimately, battery life. Through the course of the RockSHIELD development program several issues became apparent that required pragmatic solutions to manage battery life. These included monitoring frequencies for the instrument arrays and management of network connectivity to transmit information to surface servers. The system has been designed to hibernate when not polling (not a real-time system) and wake up, poll then transmit. Alternatively, the system can poll more frequently, log to the head unit and then transmit to surface every nth polling sequence. The system is therefore scalable and adaptable, depending on the use case.

A range of monitoring techniques exists to monitor ground movements occurring in and around underground excavations (Thompson et al. 1993; Kovári & Amstad 1979). More recent developments using LiDAR (Evans 2021), particularly the remote application of LiDAR using drones as well as handheld scans, has seen widespread use in underground mining. LiDAR provides a three-dimensional model of the underground excavation and, when multiple scans are employed (interferometry), LiDAR can be used to monitor convergence across large areas.

The use of SmartTTs that monitor rock mass movement into and around the excavation are seen as complementary technology to LiDAR (and other convergence monitoring). An example of a use case would be the deployment of SmartTTs in areas identified by LiDAR heat maps to confirm the depth of the plastic zone and appropriate lengths of cable/tendon reinforcement.

3 Development of the wi-fi smart telltale

The older (Generation 2) analogue Rock-ITs were not designed to integrate displacement sensors. In designing the new instrument, the essential components of the analogue system were retained; most notably, the uphole assembly consisting of a stainless steel anchor spring and wire as they are simple and proven. To incorporate the new rotatory potentiometers and printed circuit board assembly, a new collar piece incorporating a modified visual readout was developed.

3.1 Four-anchor wire extensometer

A redesigned (Generation 4) collar piece and visual readout were developed to incorporate the SmartTT sensors. The sensors comprise four rotary potentiometers (paired) that can be retrofitted to the instrument. The analogue Rock-IT can be installed around the excavation perimeter, from upholes in the backs to horizontally in the sidewalls, enabled by the tensioned spring anchors. The visual readout is still useful, both as a backup to the digital as well as for underground personnel who may not have access to tablets.

Figure 2 displays a render of the SmartTT showing the paired sensor removed from its mounting plate. Figure 3 displays a close-up of sensors removed following Stage 1 trials at Fosterville Gold Mine (FGM), and shows shafts that engage with the anchor wires, the mounting plate, and cabling with sensors able to be cleaned, calibrated and reused.

3.2 Head unit and battery pack

RockSHIELD's head unit and battery module are each 200 mm wide, 150 mm high and 74 mm deep. Figure 4 displays a render of the head unit and battery pack.

The RockSHIELD head unit includes a datalogger that can be configured via the tablet app and/or remotely via wi-fi communications and the RockSHIELD Web application from surface. The head unit can be configured for a range of sample rates specific to the use case (typically 15 minutes to 1 hour for routine displacement monitoring) and store data on board.

Key diagnostics are visible on the head unit via LED display and include battery level, wi-fi signal strength and wi-fi status.

A separate battery pack was developed to provide a level of flexibility on system use, allowing for a combination of higher logging rates (wi-fi and power usage) and/or extended monitoring life. Design life is two years, dependent on logging rate and environmental conditions. A lithium iron phosphate (LiFePo) battery chemistry was chosen, based on a range of factors including safety (chemical stability and thermal runaway), performance (energy density), recharging and cost.

The nominal battery life for the four-sensor SmartTT logging at 15 minute intervals is two years. A significant amount of work was conducted during code development for the network communications to ensure data packet size, wi-fi polling and data transmission was optimised. This is contained both within the head unit firmware as well as the RockSHIELD Web network controller.

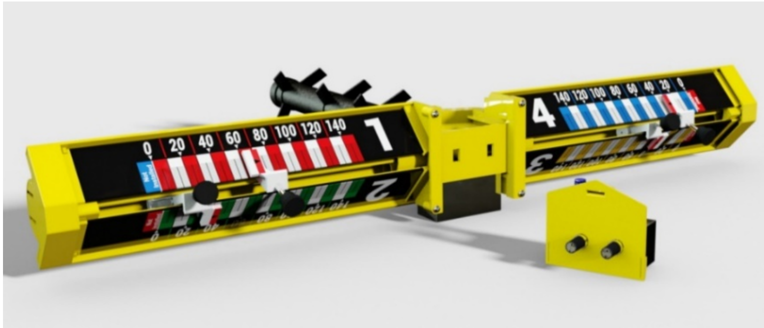

Figure 2 Render of Generation 4 SmartTT showing sensors removed from the mounting plate, allowing retrofit

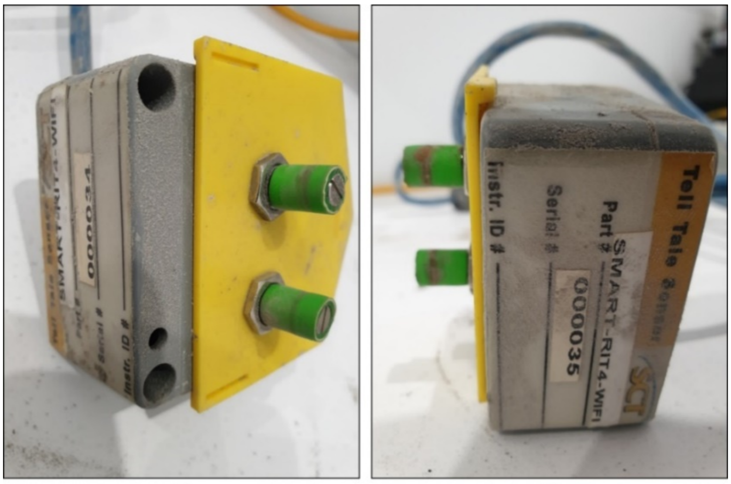

Figure 3 SmartTT sensors removed from Fosterville Gold Mine at the completion of Stage 1, prior to cleaning, calibrating and reuse

Figure 4 Head unit (logging, wi-fi, storage) and LiFePo battery pack

4 RockSHIELD software interface

4.1 Overview

The RockSHIELD software consists of:

- A tablet app that enables programming of instruments as well as local wi-fi connection underground for local mode monitoring and interrogation.
- A server-based (Rest API) database that manages network connection to instruments and storage of data.
- A graphical user interface that has different levels of authority to enable programming of alarms and other instrument parameters, display of a range of system parameters including wi-fi connectivity (system health), battery life for each instrument, and tabular and graphical data display.

As discussed later in this paper, the initial deployment of RockSHIELD at FGM did not connect to the mine wi-fi network and operated in a local wi-fi mode with the tablet application. This provides flexibility for deployment in mines without wi-fi and/or scalable to monitor locally (using a tablet) until networked wi-fi becomes available at a particular location in the mine.

Three software programs provide user programming and monitoring capabilities:

1. RockSHIELD App—a tablet application used for communicating directly with instruments, allowing a user to configure sensors, read sensor data, and export and download data to a .CSV file
2. RockSHIELD Platform—a platform composed of multiple microservices, used for collecting sensor data via underground wi-fi networks, threshold detection and hierarchical management of instruments across an entire mine network
3. RockSHIELD Web—a dashboard that enables users to monitor sensor readings and problematic locations in the mine.

4.2 RockSHIELD App

The RockSHIELD App was developed to allow for direct wi-fi connection to the head unit. It allows users to download data from the head unit for other geotechnical analyses as well as providing a graphical interface to interrogate latest movement trends.

The RockSHIELD App has also been provisioned to enable programming of the head unit firmware that assists with maintenance, software upgrades and system commissioning. Most of the instrument commissioning specific to the mine site can be conducted on the surface prior to going underground, which saves time, reduces errors and ensures work is conducted away from the production environment, thereby minimising interruptions to mining processes.

The app is intended to be used by a range of technical and production roles. For example, as a safety protocol, production personnel could log on to instruments prior to entering their work area to assess whether movement has occurred or alarms have been triggered.

A schematic display incorporated into the app shows a graphical representation of the zones of rock mass monitored. The four anchors can be placed at depths into the rock mass that correspond to the length of reinforcement elements and therefore confirm if movement exceeds support length. Anchors can be positioned to confirm depths of rock movement that may correspond to pre-determined trigger points (for use in TARPs) and/or to validate modelling or other geotechnical analyses.

Figure 5 displays examples of the schematic and stacked-column data analysis highlighting the four zones monitored into the rock mass and the ability to determine readily the depth of rock failure (plastic zone) and changes in movement.

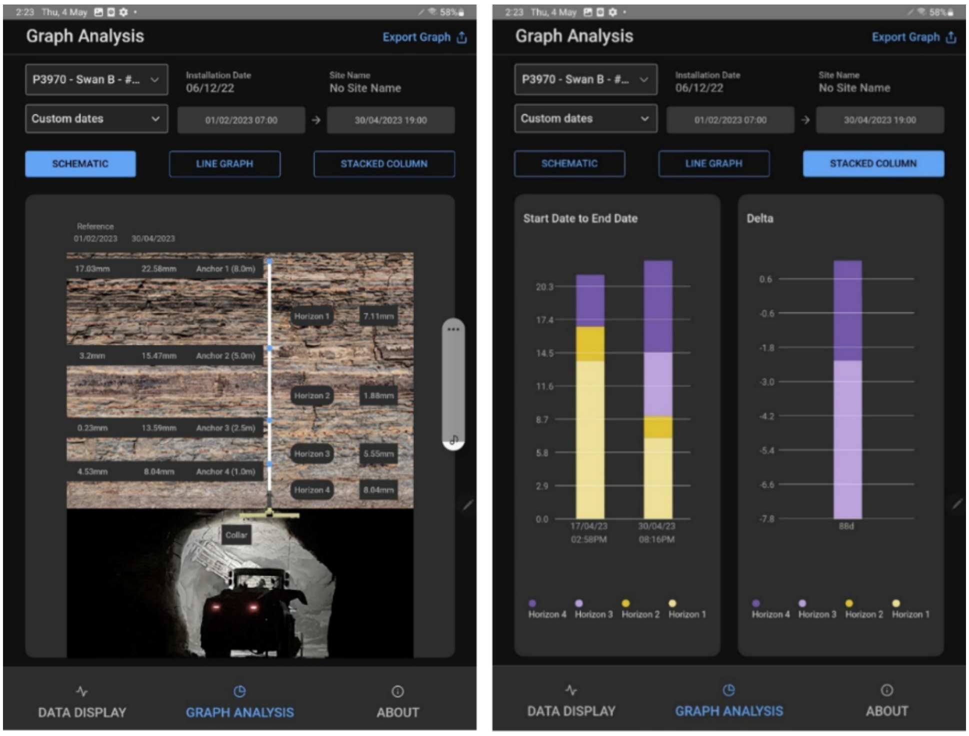

Figure 5 RockSHIELD App graphing interface showing two graphing options for schematic and stacked-column (note line graph not shown)

4.3 RockSHIELD Web

RockSHIELD Web is a software application used to remotely monitor SmartTTs. Datalogger and field sensor hardware are installed in the field and connected via a short cable. This hardware is then integrated, via the mine wi-fi network, to a data storage and management server (virtual machine) located on the mine surface. Users then view field data using RockSHIELD Web via a standard web browser connected to the mine network.

The RockSHIELD server that operates on the virtual machine is responsible for:

1. Storage of data from instrumentation sensors.
2. Hosting RockSHIELD Web software and user access management.

A full overview of the software is not possible in this paper, so a summary of key functions is provided here. RockSHIELD Web comprises a user interface designed and tested to be intuitive and with the ability to assign access levels to enable secure network access, network configuration, instrument configuration, analysis and graphing of results in real time, setting of alarm thresholds, and commissioning and decommissioning of instruments.

RockSHIELD Web provides:

- Real-time alerts when sensor readings breach pre-determined thresholds limits.
- A 3D interactive map of the sensor locations within the mine so users can quickly identify locations of concern.
- A range of graphing and analysis functions.
- Colour-coded tabular data for all instruments, based on user-defined alarm thresholds.
- Email and SMS alerting.
- System health, wi-fi connectivity and alarm status.

An example screen showing an overview of installed instruments with overall health and diagnostics is shown in Figure 6. Importantly for battery-powered sensors, the head unit logs current battery state and communicates this to the RockSHIELD Web every polling period.

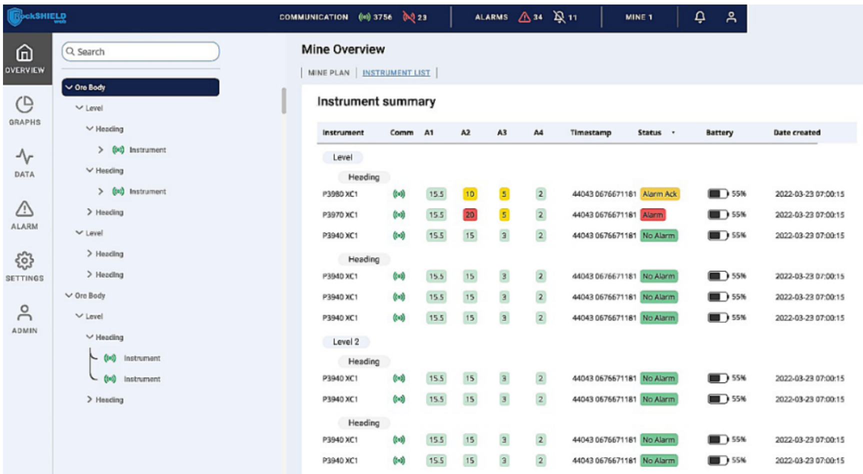

Figure 6 RockSHIELD Web overview screen showing mine hierarchy on the left and instrument readings and status on the right

Importantly, any alarms and system status are shown in the ribbon bar, and wi-fi connectivity for each sensor is visible to enable quick troubleshooting and rectification.

Instrument analysis and configuration is managed through the application, with logging rates configurable remotely and setting of alarm thresholds via horizon or overall depth into the rock mass enabled. Alarm thresholds can also be set by group, whereby all instruments in a particular geotechnical domain and/or mining level, or other similar characteristic, can be grouped.

Figure 7 displays an example of instrument analysis showing graphing options (line graph shown here) and instrument setup and status.

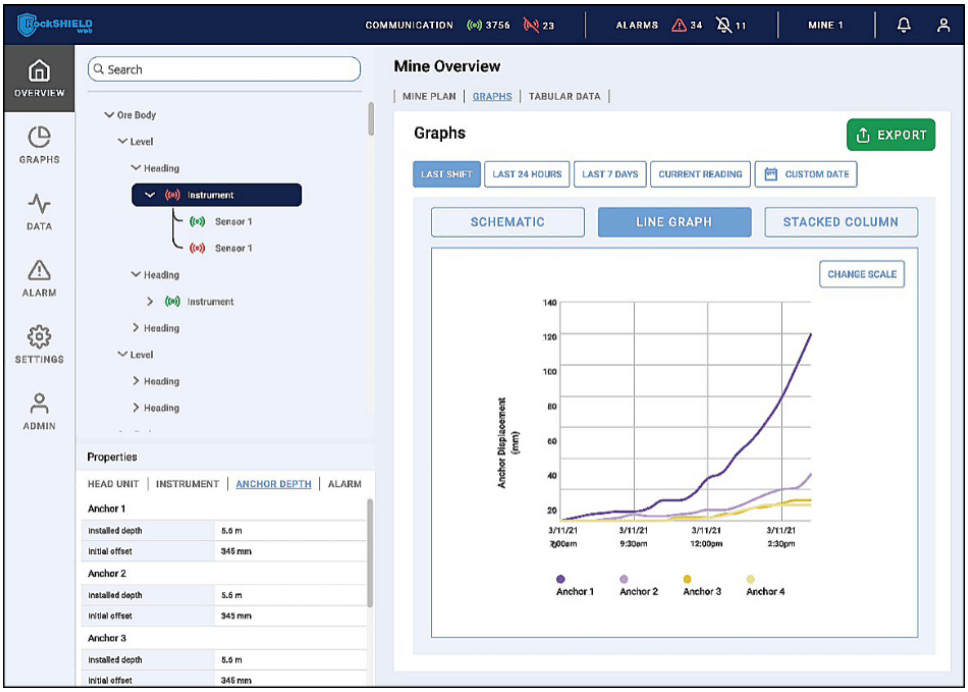

Figure 7 RockSHIELD Web instrument analysis screen showing graphing options and instrument properties and settings (including alarm settings)

5 Fosterville Gold Mine case study: analogue to digital transition

5.1 Overview

Located approximately 20 kilometres east of Bendigo in Victoria, Australia and operated by Agnico Eagle Mines, the FGM produced 338,000 ounces of gold in 2022. Mining depths are increasing to the south in the current mining areas of the Phoenix, Harrier and Swan ore bodies. Figures 8 and 9 show the location and longitudinal projection of the FGM, respectively.

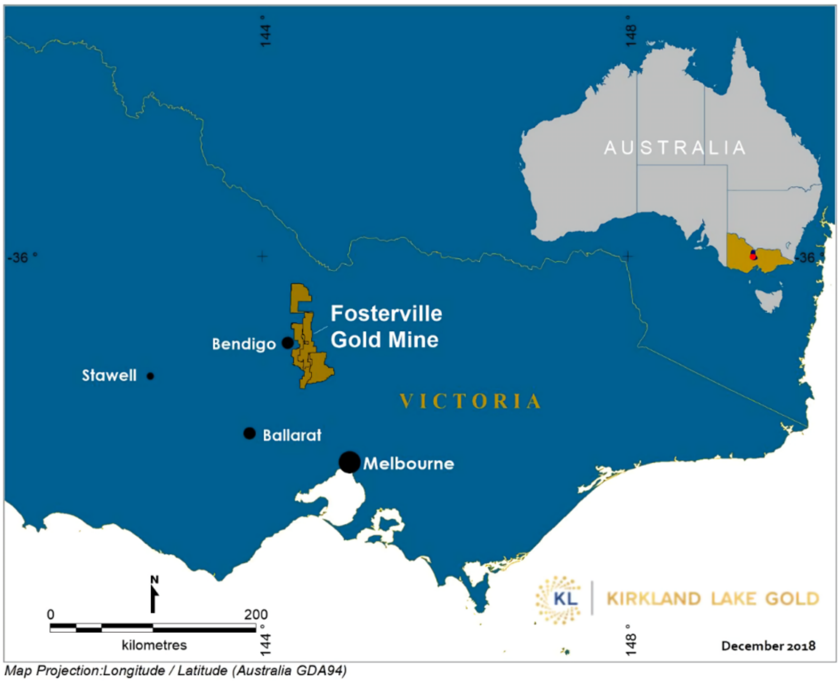

Figure 8 General location plan of Fosterville Gold Mine – Victoria, Australia (after Fuller & Hann 2019)

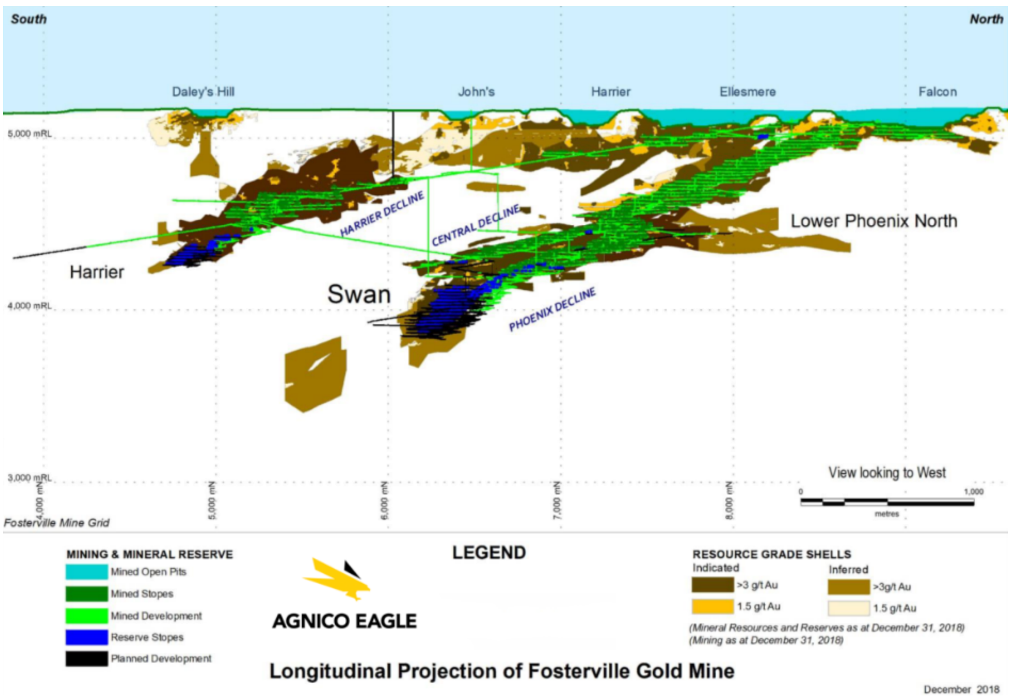

Figure 9 Long section of Fosterville Gold Mine's southern workings (after Fuller & Hann 2019)

Current mining depths below surface typically range between 1,000 to 1,400 m, with associated increases in ground stress and impacts to rock mass conditions. Historically, FGM has used two-anchor analogue Rock-IT wire extensometers to assess the level of rock mass damage (plastic zone) in ore drives during stoping activities (in conjunction with a broader monitoring strategy). Approximately 1,800 analogue Rock-ITs were installed over a 10-year period from 2012.

In 2020–2021, the implementation of a mine-wide wi-fi network at FGM using a system from Northern Lights Technology framework provided opportunity to investigate options for improved geotechnical monitoring. In 2021, SCT approached the rock mechanics team at FGM to discuss opportunities to conduct staged trials of a new IoT platform being developed by SCT as part of a staged digital transformation. Working with the FGM team, SCT outlined and conducted a staged program of hardware and software development.

Key objectives of the project included:

- Transition of routine monitoring from analogue two-anchor Rock-ITs to digital four-anchor SmartTTs.
- Provision of continuous access to data for production and technical personnel through tablet and PC applications.
- Integration with, and complementing, other forms of ground monitoring including LiDAR.
- Assisting with quantifying, and validating, depth of plastic deformation around the excavations during stoping activities.
- Providing quantitative data to assist with the design of ground support and associated excavation performance.

Numerical simulation of rock mass damage showed a noticeable increase in the depth of the plastic zone in ore drives in future mining areas. Assessment of anticipated ground support performance, including the length, capacity and timing of ground support, would be assisted with a more complete understanding of the progression of damage around the excavations.

Quantification on the timing, magnitude and depth of rock movement is expected to assist with design and specification of ground reinforcement and ensure the timely installation of optimised support in future mining areas. Measurement of ground movements into the rock mass are complementary to existing ground monitoring, including tunnel surface movements (LiDAR) and areas of microseismic activity.

The SCT and FGM teams outlined two broad stages to the project:

Stage 1 – Proof of concept

- Standalone system comprising 10 four-anchor SmartTT.
- Instruments log and interface via wi-fi in local mode to FGM Samsung tablets.
- Assess configurations of instrumentation arrays around the tunnel profile.
- Test duty cycle and system performance at various logging rates.
- Develop and deploy RockSHIELD App software interface.

Stage 2 – Network deployment and web interface

- Integrated network of 10 four-anchor SmartTT deployed on the FGM 2.4 GHz production network.
- Development of REST API web software (RockSHIELD Web) to interface and manage instrumentation array from a surface-based network server.
- Optimise logging (head unit) and instrument configuration including cabling for ease of installation.

5.2 Stage 1 – local mode and proof of concept

Stage 1 installation commenced in November 2021, with hardware operating until June 2022, following successful completion of Stage 1 goals and stoping in and about the instrumentation arrays. Blasting and stoping adjacent to the instruments is a practical consideration and potential hazard to their survivability. During Stage 1 (and Stage 2) no instruments were lost to blast damage, with instruments typically being removed 5–10 m from the stoping front (adjacent to the next stope).

Figure 10 displays an image of an instrumentation site from Stage 1 that includes a prototype 3D printed head unit housing and an optional 25 m cable extension. The cable extensions were trialled in Stage 1 to assess and mitigate potential blasting damage. Figure 10b shows typical blasted stope highlighting brow and drive conditions.

(a) (b)

Figure 10 Stage 1 installation. (a) Prototype head unit and 25 m cable extension; (b) Typical blasted stope

In total for Stage 1, RockSHIELD SmartTTs were deployed at five underground locations, including arrays of up to three instruments per oredrive section (back and haunches). The SmartTT utilises tension springs that enable instruments to be installed from horizontal to vertical installations.

Optimisation of the RockSHIELD App software through Stage 1 saw up to Version 47 developed with a priority focus on optimisation of data packet size during wi-fi transfer and associated battery life. Additional capability was added through the inclusion of graphing functions (in addition to tabular data display).

Rock mass deformation was successfully recorded into the rock mass at various depths during blasting and stoping cycles. Movement was detected at all five locations. Four locations returned displacements of 1–10 mm, while one location returned displacement of 27–30 mm.

Over the eight-month Stage 1 monitoring period, using typical data logging rates of 45 minute intervals, the 11.6 Ah batteries performed well and had greater than 50% battery life at completion of the trial, consistent with the nominal design life of two years.

5.3 Stage 2 – network deployment

Finalisation of Stage 2 instrumentation design occurred through early 2022, with learnings from Stage 1 incorporated into the final design. Key design upgrades included optimisation of the firmware on both the

SmartTT and head unit to trim data packet size, and communication protocols to ensure efficient communication over the FGM wi-fi network to surface.

Figure 11 displays programming and factory acceptance testing of the Stage 2 FGM instrumentation at SCT.

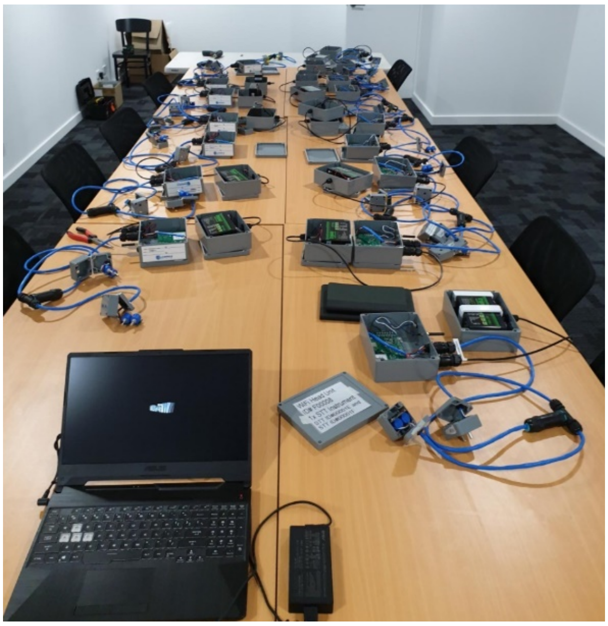

Figure 11 Stage 2 firmware installation and factory acceptance testing

Site installation for Stage 2 on the FGM 2.4 GHz production network began in October 2022. FGM personnel selected a total of 10 separate sites for monitoring in and adjacent to future stoping areas. Instrumentation was installed by Paul Seaward (SCT) in conjunction with FGM's Steve Robinson.

The secondary support crew had pre-drilled 8 m-long boreholes and a telehandler with basket was used for the installation. Following a review of Stage 1 outcomes, and without the requirement to locally access the head unit, it was decided to install the head unit and battery packs on the backs adjacent to the SmartTT instruments. Figure 12 displays an example of the Stage 2 installation.

As noted, installation commenced in October 2022, and instrumentation continues to operate where installed. Several units have been removed (decommissioned) as stoping fronts advance. Decommissioned instruments are checked over, programmed, tested and brought back into service in new locations. An example of a recovered head unit and battery module is shown in Figure 13.

Figure 12 Stage 2 SmartTT and RockSHIELD head unit and battery module at Fosterville Gold Mine

Figure 13 Recovered Stage 2 head unit and battery module prior to cleaning, reprogramming and recommissioning underground

5.4 mXrap integration

Through the course of the project with FGM, a request was made from site technical personnel to provide real-time integration of RockSHIELD SmartTT data into mXrap. The main benefit of the integration was consolidating a range of geotechnical data sources on one platform. The team at mXrap (notably Liam Niedzielski and Dr Matthew Heinsen Egan) developed a range of scripts to feed data from the RockSHIELD Web REST API to the mXrap server in real time.

Figure 14 shows a screen capture of the FGM mXrap screen of a four-anchor SmartTT showing time versus displacement. Key changes in ground response are apparent, indicating an increasing depth of plastic zone with time/mining activity.

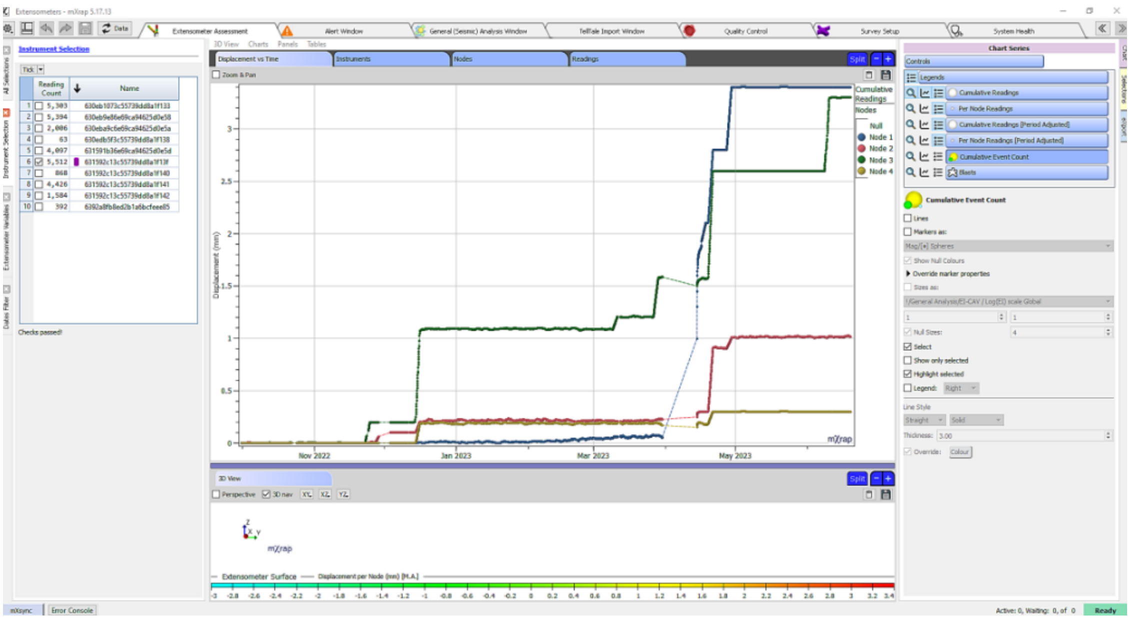

Figure 14 Fosterville Gold Mine mXrap and RockSHIELD integration via automatic scripting and REST API Note increase in movement in deeper regions around the oredrive due to adjacent stoping activity

As with all measuring systems, there are a range of systemic and non-systemic errors that may impact performance of the system. For the SmartTT this includes slippage of anchors within the borehole, rock mass movement that may loosen anchorage and/or shear the borehole, and the resolution of the rotary potentiometer (among other factors). The vertical axis on Figure 14 shows 0.5 mm vertical graduations and it is apparent that some 'negative' movement is occurring on Node 3 (green), nominally 0.1 mm. Experience to date with the system at FGM suggests that the repeatability of a single node is approximately 0.3 mm, which is considered reasonable for the intended application.

6 Conclusion

This paper outlined an 18-month program of work to successfully transition analogue multi-point borehole extensometers (Rock-IT) to a wi-fi enabled digital logging platform. A staged implementation at FGM allowed for the deployment of the system using handheld tablets in a wi-fi denied environment through to full network connectivity over a 2.4 GHz production network and web-hosted platform.

Results from the project confirmed the ability to record the timing, failure mode and magnitude of ground movement into the rock mass around excavations. Dynamic events associated with stope firing were recorded and the ongoing progression of rock mass movement at depth into the rock mass was observed.

Acknowledgement

The assistance and foresight of the Rock Mechanics and IT team at FGM are gratefully acknowledged here: Matthew Farrington, Steve Robinson, Daniel Tatti, Corey McKenzie and Alan Hitchcock.

The SCT and related teams delivered a robust and mine specification IoT platform in short order: Paul Seaward, Jim Simonovski, Chris Cassar, David Eluisha and Robin Tang.

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