ANVÄNDNING AV GRUNDPROBE GML LIDAR SCANNER FÖR ATT MÄTA RESPONEN PÅ EN CEMENTERAD GRUVMATERIAL BARRIÄRER UNDER ÅTERFYLLNINGEN AV BHP OLYMPIC DAM MINE

Using the GroundProbe GML LiDAR Scanner to measure the response of cemented mine fill barricades during Backfilling at BHP Olympic Dam mine

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Abstract

Light detection and ranging systems (LiDAR) have grown in popularity in recent years for the measurement of ground convergence over time in underground mines. These systems are typically used to manage geotechnical risk associated with rock mass displacement caused by mining induced stress redistribution.

The Olympic Dam mine is a large poly-metallic underground mine located in South Australia, 550 km NNW of Adelaide. It is the fourth largest copper deposit and the largest known single deposit of uranium in the world.

The GroundProbe Geotechnical Monitoring LiDAR (GML) system has been applied in a unique application at Olympic Dam mine to measure, with sub-millimetre accuracy, bulking/deflection as a result of the load experienced by a cemented mine fill barricade during backfilling.

Many attempts have been made to model the capacity and response of cemented mine fill barricades in the past using complex non-linear numerical modelling methods which are required to model both plain and reinforced concrete behaviour (Grabinsky et al, 2014). The GroundProbe GML system measures surface displacement in near-real time with full spatial resolution and submillimetre range resolution. With this new technology, the aim of the project was to test and optimise existing backfill processes in the hope to increase the rate of fill placement hence permitting faster turnover of stopes and earlier access to adjacent mining blocks.

1   Introduction

Olympic Dam mine is a polymetallic underground mine located 550 km NNW of Adelaide in South Australia. It is the fourth largest copper deposit and the second largest uranium producing mine in the world. The mine opened in 1988 and has been owned and operated by BHP since 2005.

Ore is mined via conventional longhole open stoping with cemented aggregate fill (CAF). As the mine has matured, stope sizes have typically reduced in size by about half. Stope sizes are expected to become more variable in size in the future in response due to expansion into new mining areas, the expectation of more challenging ground conditions, and hence the requirement for a more 'surgical' approach to stope design and extraction. In order to maintain future production rates, a greater number of stopes must be mined concurrently. As such, the mine must become more proficient at turning stopes over, seizing opportunities to optimise the process wherever possible.

One area of key focus for optimisation is the backfill process. If stopes can be filled more rapidly, the mine will be better able to meet its future goal of mining a greater number of smaller stopes concurrently.

Initial testing of a new fill strategy as described below, has shown a reduction in stope fill time by up to 20% compared to the previous "controlled fill" strategy. This change will enable stopes to be turned over faster, allowing more efficient re-entry to new stoping areas, hence facilitating future production profiles / business requirements.

A number of controls are already in place to mitigate (or eliminate) any possible additional risk associated with any change in fill strategy including the use of pressure sensors to ensure hydrostatic pressure behind the barricades does not meet or exceed the design specifications. Also, and perhaps most importantly, an exclusion zone is enforced as a mandatory requirement under State Legislation, to eliminate any risk to personnel until the fill reaches a strength where it becomes 'self-supporting'.

Further research into the backfill process may present opportunities to further optimise the process and speed up filling time beyond the new fill regime. The GroundProbe GML system has been trialled on site to investigate any future opportunity to optimise processes further, adding an additional level of monitoring on top of existing risk management controls

The purpose of the GML trial was to, essentially:

- Test the system as fit for purpose and demonstrate 'proof of concept'
- Test the practicability of remote monitoring in near real-time given the existing exclusion zone around the void being filled
- Develop a plan for further testing and consideration of future opportunities to optimise processes with this additional control in place

The CAF used at Olympic Dam mine consists of either de-slimed neutralised tailings or dune sand, 40mm limestone aggregate, water and Ordinary Portland (OP) cement. Design UCS range is from 0.5MPa – 2.0MPa, dependent on factors such as future requirement to mine adjacent to exposed fill surfaces (adjacent stopes), expected future requirement to mine drifts through the fill and relative level/location within the stope.

CAF Filling is an integral part of the mining cycle, allowing new stopes to be extracted safely without sterilising adjacent ore. The use of hydraulic or cemented fill is recognised as a hazardous activity and elimination of risk to site personnel presents as the highest priority when considering any change management. This study was commissioned to ensure safety is maintained with increased rates of fill placement.

Barricades are generally designed based on the expected pressures experienced by the barricade due to the fill mass behind. These assumptions are then validated by conducting in-situ pressure measurements on barricades during filling. This trial has investigated the strain component of barricade design, with the potential to validate previous modelling data.

2   Backfill System at Olympic Dam Mine

Backfill is a critical component of the underground mining operations at Olympic Dam mine. The mining method and sequence requires all stopes be filled with backfill in a timely manner, to maintain both local and regional mine stability, and to maximize ore extraction (Figure 1).
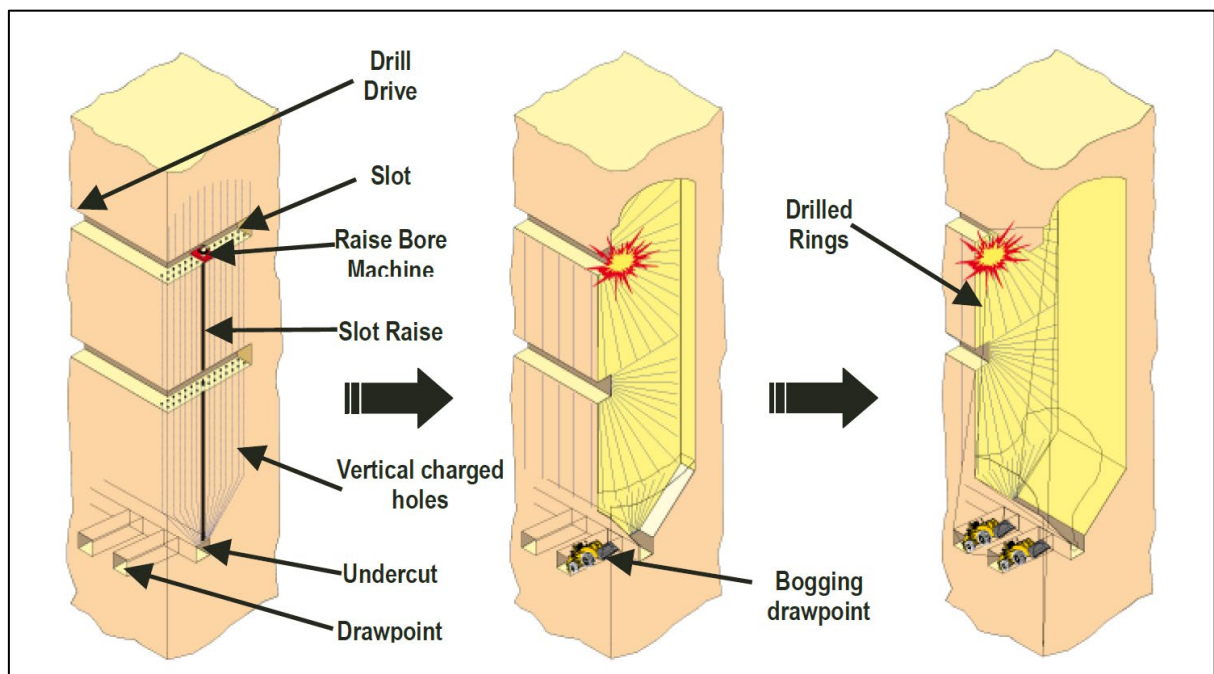

Figure 1 Stoping method at Olympic Dam mine

2.1 Backfill Demand

Stopes are backfilled using rock fill and cemented aggregate fill individually or a combination of both. CAF is the primary backfilling material with an annual production of 2.2 - 2.3 million cubic metres.

2.2 CAF Plant

The CAF plant has a design capacity of 380-435 cubic metres per hour. The current CAF operations at Olympic Dam mine include the following major components:

- Onsite quarry to produce 40mm coarse aggregate material
- Dune sand as fine sand material or
- De-slimed Neutralised tailings (NTS) as a fine material from the hydro-metallurgical plant
- Slag cement supply and storage
- Water from onsite dam
- CAF batching plant
- Fleet of surface trucks for CAF delivery
- Stope specific surface boreholes for CAF placement
- Shotcrete barricades to contain freshly placed CAF

OD has developed specific CAF mix recipes based on dune sand and mine tailings with target strengths varying from 0.5MPa to 2.0 MPa at 90-day cure age using 0.5 MPa increments.

2.3 Delivery and Placement

Owing to its high solids mix density and high internal friction, CAF has limited flow capability due to high rate of consolidation, and therefore cannot be reticulated laterally for long distances via pipelines. CAF is therefore placed into open stopes using dedicated boreholes drilled from surface to the crown of each stopes being filled.

CAF is delivered to surface boreholes by a large fleet of 15 m^3 capacity bottom discharge trucks.

2.4 Barricades

Arched shotcrete barricades are used to retain freshly placed CAF in stopes.

The barricade design factor of safety (FoS) of 2.0 is based on the geostatic load exerted by 8m high uncured CAF pressure (170 kPa) acting on the barricades assuming bulk density of 21.5 kN/m^3 for uncured CAF (BGMC,2018).

Barricades are created by spraying shotcrete onto prefabricated steel formworks. Olympic Dam mine uses a standard shotcrete thickness dependent on barricade dimensions with 22 MPa characteristic UCS. Shotcrete barricades are cured for a minimum of three (3) days to achieve the required minimum 22 MPa UCS before filling commences.

Olympic Dam mine applies a strict regime of checklists, controls and approvals to ensure the barricades have been constructed to specification and design.

2.5   Pressure Monitoring

Olympic Dam mine has initiated a pressure monitoring program commenced in late 2016. The instrumentation consists of piezometers for measuring pore water pressure and total pressure cells for determining lateral earth pressures.

The results to date indicate that:

- The maximum pore water pressure measured was 20-34 kPa
- The maximum horizontal pressures measured was 33-59 kPa
- A large rise in pressure was not registered once the continuous pour commenced

The results confirm that the lateral barricade pressures at Olympic Dam mine are generally limited. This is due to the coupled effect of development of effective stresses as a result of water dissipation and early-age shear strength gain due to cement hydration, which limits the lateral pressures exerted on the barricades by making backfill self-supporting and by mobilising shear strength along the perimeter of the stope due to arching.

3   **Backfill Strategy Review**

Olympic Dam mine recently completed an independent review of the existing backfill strategy with an aim to optimise filling operations (BGMC, 2018). The GML monitoring project as described in this paper was conducted independent of this review. The study included a detailed review of the existing filling practices, including barricade design and construction. This also included review of pressure monitoring results to confirm barricade design loads, early age CAF strength results to select a suitable filling regime that will match the barricade design capacity with the expected fill pressures without jeopardising safety and efficiency.

To provide basis for recommendations made, the review included the following prerequisite tasks and activities:

- Detailed operational review
- Test work for early age CAF and shotcrete UCS
- Instrumentation and monitoring

3.2 Current filling regime

The current filling regime involves filling the stopes in "Controlled" and "Continuous" fill runs. The Controlled filling is specified in both maximum vertical rate of rise and maximum fill volume per run (whichever is smallest) followed by a fill pause period. The Continuous fill runs are specified in maximum volume per shift with no fill pausing.

The existing backfill strategy was developed more than a decade ago and has been successfully applied since, without any major issues. However, it was noted that the same strategy has been used despite implementation of the arched shotcrete barricade design and there was potential to increase fill placement whilst maintaining safety.

The current fill regime includes:

Controlled Pours
- − Commences once CAF is at Floor level for Draw points and 1m below Floor level on other levels
- − Concludes once CAF is 2m above barricades
- Draw points & Mid-levels
  - − 1m of rise (or 1,000m^3 - whichever is smaller) then 4 hours pause

- Crown levels
  - − During rise of first 3m behind the barricade: 1m of rise (or 500m^3 - whichever is smaller) then 4 hours pause
  - − Above 3m: "Tight-filling" stages - 500m^3 then 20 hours pause
- Continuous Pours
  - − Between levels with a maximum volume of 3,000m^3 per shift
- Exclusion Zones (erection of "No Travel" signs) at minimum of 50m around the active fill zone
  - − Commence once CAF level is 5m below Floor
  - − Conclude 12 hours after CAF level is 5m above the Backs

3.3 Proposed Filling Regime

Mobilisation of uncured CAF as a result of a barricade failure is recognised as a potential safety hazard and can lead to significant consequences, including but not limited to: risk to personnel within 50m of the potential burst point, potential production loss and mine scheduling delays. Olympic Dam mine recognises these risks and has conducted this trial of the GML monitoring system as an additional control - above and beyond what is expected as being required to reduce the risk to as low as reasonably possibly and within acceptable limits.

The primary objective of adopting an appropriate filling strategy is to control barricade loads and prevent any risk of fill inrush due to barricade failure; with the primary focus being to maintain safe working conditions, while at the same time increasing productivity and reducing cost.

In order to achieve this outcome, the following controls are in place:
- Appropriately engineered barricade design, construction and quality assurance and control;
- Fill management strategy that includes an appropriate fill placement regime; and
- Quality control, instrumentation and monitoring including pressure sensors and the GML system (GML for trial purposes only).

A simple and more efficient filling regime specified in vertical rate of rise rather than run volume were recommended because it is not affected by changes in stope size and filling rate (BGMC, 2018).

The proposed fill regime can be described simply by two distinct processes: Plug Pours, and Body Pours separated by adequate cure time to prevent backfill flowing in the event of a failure of a barricade during the subsequent Body Pour. The filling regime is summarised as follows:

For draw points:

- Plug Pour
    - continuous controlled filling at maximum 8m vertical fill rise rate per day followed by a plug cure period of minimum 2 days to create a Plug with minimum UCS of 200 kPa
- Body Pour
    - continuous controlled filling at maximum 12m vertical fill rise rate per day until the fill level reaches the floor of the barricade in the sublevel above

For mid-levels:

- Plug Pour
    - continuous controlled filling at maximum 12m vertical fill rise rate per day followed by a plug cure period of minimum 2 days to create a Plug with minimum UCS of 200 kPa
- Body Pour
    - continuous controlled filling at maximum 12m vertical fill rise rate per day until the fill level reaches the floor of the barricade in the sublevel above

For crown levels:
- Plug Pour:
    - continuous controlled filing at maximum 8m vertical rate of rise per day and a plug cure period of minimum 5 days to create a Plug with minimum UCS of 450 kPa
- Body Pour (tight-fill)
    - continuous controlled filling at maximum 8m vertical fill rise rate per day until fill completion

The Exclusion Zones (minimum 50m from stope void) are to be maintained until CAF passes 2-3m above the brow and removed after the last CAF pour in the draw point reaches a UCS strength that is at least equivalent to the barricade design pressure capacity of 170 kPa.

The proposed filling regime has the following advantages:

- Simple and more efficient fill management
- Improved fill monitoring and operational controls
- Reduced fill cycles due to faster filling rates
- Improved CAF plant utilisation and reduced operating costs
- Improved production schedule flexibility due to shorter fill cycles, and
- Potential for higher mining rates.
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Note that the figures below represent an optimum time frame based on a base stope shape and do not consider production requirements

4.   The Geotechnical Monitoring LiDAR System (GML)

Monitoring of convergence around tunnels in underground mining operations has gained increased focus in recent times with the application of survey instruments, adapted to serve as geotechnical monitoring tools. Third party software is often used to display and measure the relative displacement of points on the excavation surface for geotechnical analysis and interpretation. These and other monitoring tools are limited in their application due to issues such spatial coverage, large data file sizes and, in particular, lack of precision to be able to detect small convergence or displacement rates of up to 1mm per day within a short time window.

Using low precision instruments with high noise thresholds, means that a greater amount of time will be required before the user can identify or report with any degree of confidence, the rate of convergence/displacement or any change in that rate.

Manual processing of data, as is commonly required with raw survey data used for measurement of convergence in a tunnel, introduces the risk of human error with manual co-registration of point clouds.

Traditional convergence monitoring systems applying LiDAR technology typically involve the use of an electronic total station to measure rings of reflectors around the surface lining of a tunnel with variable precision and limited spatial resolution.

From Campbell et al 2017, "Kontogianni et.al. [3] from the IGME – Greek Institute of Geology and Mineral Exploration . . . in her controlled experiments she measured the total measurement error stack from a total station between readings from a variety of commonly used prisms and retro reflectors. Her results showed errors from non-prismatic reflectors to be as high as +/-13mm from reflectors at ranges commonly used in tunnel convergence monitoring."

For long term mine-scale monitoring of convergence in tunnels, precision with an error stack this high has generally been considered acceptable (depending on the application). Where sub-millimetre deflection is potentially expected over a time window of approximately 72 hours as was the case for this experiment, evidently a far more precise measurement tool is required.

The GML system is a state-of-the-art LiDAR based remote sensing system with the ability to track and measure surface displacements as small as 1/100th of a millimetre, with a maximum and typical noise threshold of 0.4mm (continuous fixed-point monitoring). The GML processing algorithm generates full spatial resolution data set overlaying a deformation data image on an amplitude image which serves essentially as a photograph of the area being scanned. New amplitude images are collected with every scan which is taken approximately every 20 minutes. Data 'noise' introduced by ground support elements such as wire mesh and other metal infrastructure is automatically removed by a sophisticated processing algorithm. Incidence angle issues and vector loss is overcome with this processing method and the (assumed) true deformation vector magnitude, perpendicular to the surface, is presented in the output.

The GML system is powered by either internal or external batteries or connected directly to mine power. In the case of this experiment, battery packs were required to be located greater than 50m from the scanner itself to allow full remote operation outside of the filling exclusion zone. The scanner monitored continuously, processing data scan by scan, with a full scan taken approximately every 20 minutes. Engineers were able to communicate with the processing computer which was mounted beside the scanner using a 50m cat 5 ethernet cable.

5.   Project Outline

The GroundProbe GML system was considered suitable for the project given its

- Capability to be operated remotely eliminating risk of human exposure within the fill exclusion zone
- Very high precision (0.01 – 0.4mm) which was assumed required to detect the very small deflection that may occur within the time window
- Ability to generate a data set with full spatial resolution.

Equipment suitability was assessed for the purpose of this experiment with the following criteria;

Battery life
Battery life proved to be greater than the technical specifications outlined as required. Typical power consumption requirements of the system allowed up to 14 hours of continuous use with the battery pack provided.

Data can be viewed in real time remotely via Wi-Fi and/or at the GML site
Data was available remotely via connection to a laptop outside of the exclusion zone. Data can also be transmitted directly to surface via RJ45 cable to the site fibre optic network. Processed scan file size is typically less than 3Mb allowing data transfer to any remote location.

Continuous data acquisition
Scan time was approximately 6 minutes, taken every 22 minutes, with processing time roughly equivalent to scan time, producing data in near real-time scan by scan.

Sub-millimetre precision
The ability to measure with sub-millimetre precision was demonstrated during monitoring of the curing shrinkage that occurred after the construction of the SC170 barricade. Laboratory experiments have also repeatedly demonstrated system specifications regarding precision capability.

Software automatically generates a deformation "heat map" with full spatial resolution allowing the user the select and analysis specific regions within the scan area;
GroundProbe SSR Viewer 9 software provides this functionality to view and analyse the GML data.

Customisable alarm windows with adjustable alarm thresholds
Although not relevant for this experiment, it is expected that to maximise the rate of fill pouring and further reduce the likelihood of barricade failure, real time alerts to a remote operator may be a valuable feature. Automated deformation or velocity alarms can be configured for the GML system in the SSR Viewer software.

Equipment is robust and well suited to the mining environment;
The GML system has been proven to be robust enough to function effectively with minimal maintenance requirements over the long term in a typical underground mining environment.

Equipment is safe to use – laser exposure/manual handling/safe voltages/etc
The laser itself is a class 2R, limited exposure directly to the eye will cause no harm, avoid long term exposure. The Voltages are all ELV (extra low voltage) and require no special handling requirements.
The scanner has safety mechanisms to prevent risk of injury at any pinch points.

5.1   Operational Setup

Barricades were monitored at two stopes, the "Cyan 130" and "Scarlet 170". Unfortunately, an error in the data storage meant the monitoring of the Scarlet 170 stope barricade was interrupted and there was no data collected during the actual filling of the stope, only during the construction of the barricade itself. This issue was rectified on site by the GML technician.

The GML scanner was mounted on the side wall (Figure 4) in each instance at approximately 15 metres from the barricades, with power supplied remotely from battery packs. Data was viewed remotely, outside the required minimum 50m exclusion zone, with raw data transferred via local Wi-Fi to the processing computer underground from an internal SD card and by RJ45 cable to a remote monitoring computer.

Figure 2 GML System and processing computer setup for continuous monitoring

5.2   Scarlet 170 Barricade monitoring.

The 26 Scarlet monitoring commenced on November 24th at around 7pm and concluded on December 4th at around 11am. A power disruption meant there was no data collected during the actual pouring of the backfill. However, a valuable data set was collected during the barricade construction and the curing process. The thickness of the barricade itself was measured and very minor positive displacement was measured up to 1mm during curing with shrinkage observed and measured over the 24 hours after construction (Figure 5). Signal amplitude can be seen to drop over time as the shotcrete cures and positive displacement was measured (towards the scanner) due to the shrinkage and in a direction as would be expected given the geometry of the barricade itself.
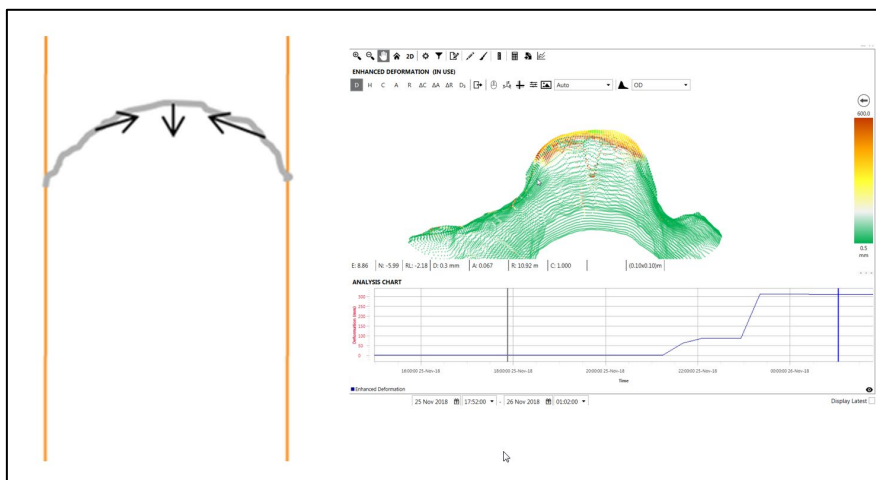
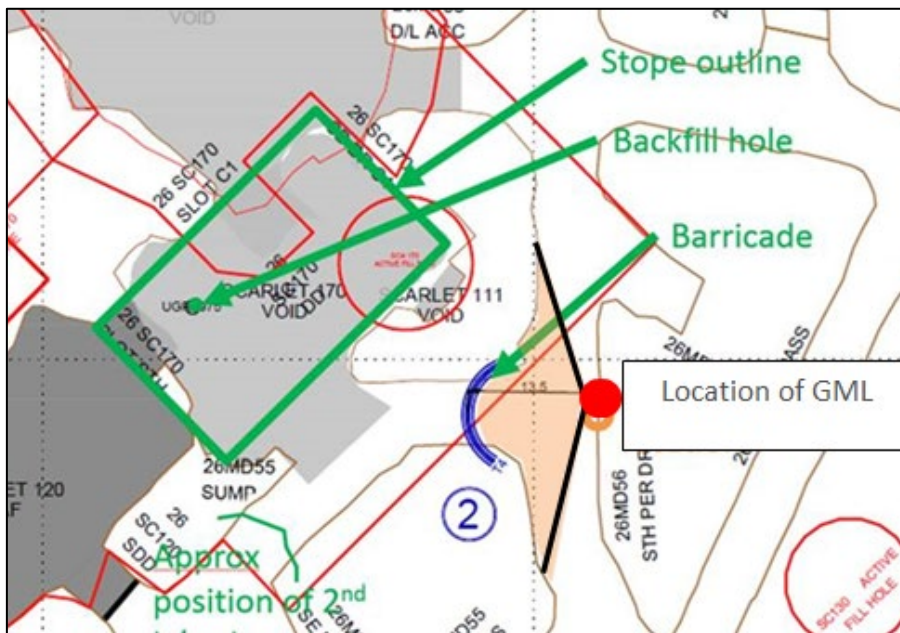**Figure 3 Positive deflection measured during the curing of the shotcrete barricade**

Figure 4 GML scanner location shown in plan-view relative to the barricade and stope
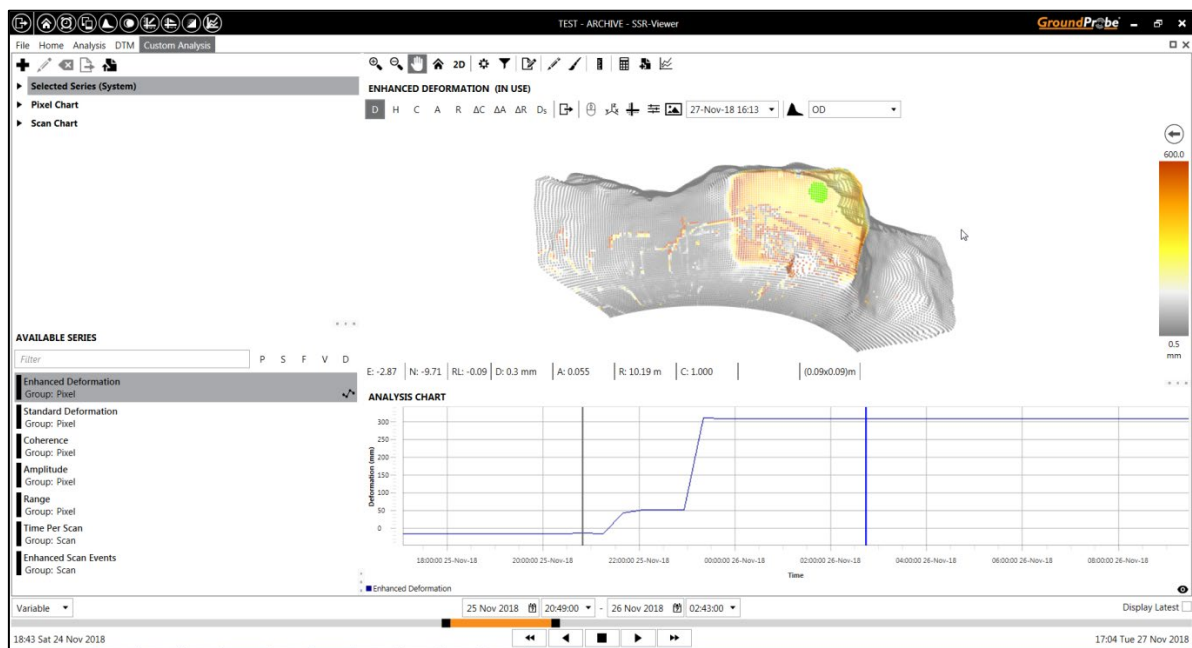

Figure 5 3D view in SSR Viewer software showing measured barricade thickness after construction

During the 48-hour period after the shotcrete barricade was sprayed a clear linear to regressive deformation trend was observed focused primarily in the centre of the barricade, with magnitude measured up to 2.8mm.
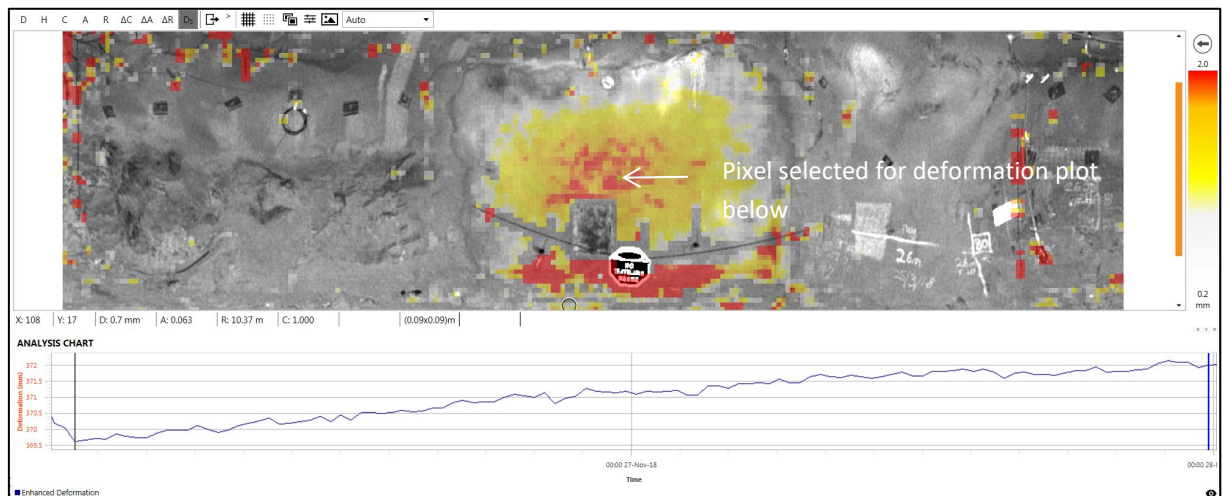
Figure 6 Deformation plot and overlay of deformation image during curing of shotcrete barricade due to shrinkage showing regressive deformation trend over 48 hours. Scale is to 2mm and noise threshold applied at 0.2mm

Another key metric measured by the GML scanner is coherence. A drop-in coherence can occur with a change in the physical appearance of the surface of the rock often associated with micro-fracturing. Coherence is related amplitude and range as measured across the pixel and a drop-in coherence is often an indication of some damage to the rock mass (or shotcrete in this instance). The image below shows the delta coherence image overlay during the 48-hour period during curing. There has been a slight drop in coherence in the centre region of the barricade. This region correlates reasonably well with the zone of maximum deflection. Slight drops in coherence were also observed which correlate well with apparent geological structural features in the side walls.
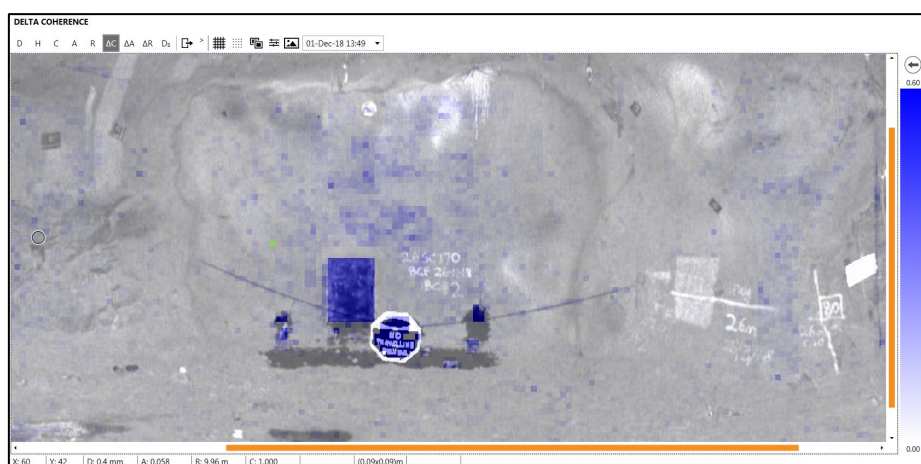

Figure 7 Delta coherence image overlay showing drops in coherence during the 48 hours curing period after barricade construction

5.3 Cyan 130 barricade monitoring results

The 46 Cyan 130 barricade that was monitored during filling was constructed on August 4th, 2018 with monitoring of the filling process commencing on December 4th and continuing until December 11th. From the GML data analysis it can be confirmed that no significant or measurable

deflection/deformation occurred on the surface of the barricade during either the Plug Pour or the Body Pour. This result supports the findings of FLAC3D modelling which indicated that the 350mm thick arched fibrecrete barricade will begin to yield at a load of between 300 kPa and 400 kPa (approximately 350 kPa) which includes a safety factor of at least two (2.0) to account for variability in fibrecrete properties, modelling methodology and variability in the rock-wall interface. The modelling predicted displacement of less than 1.0mm displacement and less than 2.5 MPa compressive stress when subject to 170 kPa fill pressure.

The Plug Pour for Cyan 130 commenced during night shift on 6th December. Water seepage can be seen through the rock-wall interface and through the observation portal in the GML data. The observation door itself is seen to move towards the scanner approximately 15mm as the fill comes into contact with the barricade at approximately 21:30 on 7th December (Figure 11). The GML results indicate that there is no measurable deflection or deformation on any other part of the barricade during the Plug Pour.
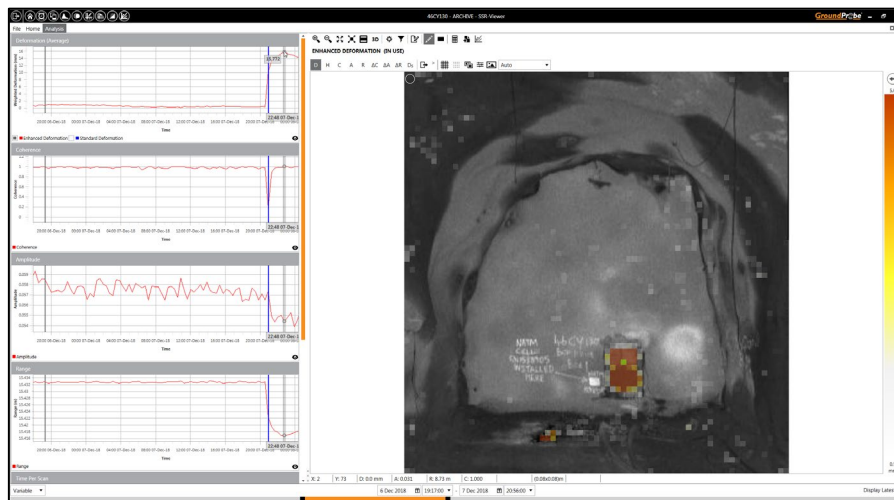

Figure 8 15mm measured deflection of the observation door at the point where fill reached the barricade during the Plug Pour

The Plug Pour was completed during night shift on 8th December and was then left to cure over a 48-hour period before commencement of the Body Pour on 10th December. During this curing period the water on the barricade can be seen to dry out from the GML amplitude images. On December 10th water can be seen again to seep through the rock-wall interface indicating commencement of the Body Pour.

During the Body Pour, water can again be seen to seep through the rock-wall interface, the drainage pipe and also through what appear to be cracks or other structures in the barricade. Again, no indication of measurable deflection or displacement was observed during the Body Pour. It is uncertain but assumed that these apparent structures may be either an artefact caused by the construction process or simply due to variability in the shotcrete material itself. There is no indication from the displacement data that tensile failure, fracturing or cracking has occurred during the filling of the stope. The average cumulative deformation over the entire barricade during both stages of filling was less than the specified maximum noise threshold of the GML system of 0.4mm, with an observed noise threshold of approximately half that at +/- 0.2mm.

Careful analysis of individual pixels either side of these apparent "cracks" shows conclusively that there was no measurable deflection or precursor movement observed or measured during filling. The coherence image from the GML confirms also that there is no indication of cracking or degradation of the surface. Inspection of the barricade after filling also showed no visible signs of cracking.
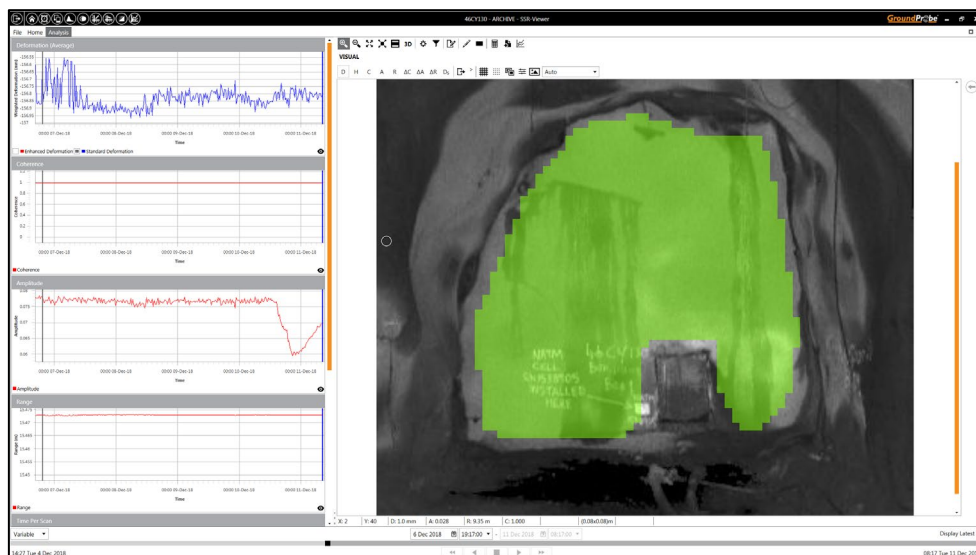

Figure 9 Deformation plot and amplitude image during the complete Plug and Body Pour demonstrating no measurable deformation across the barricade.
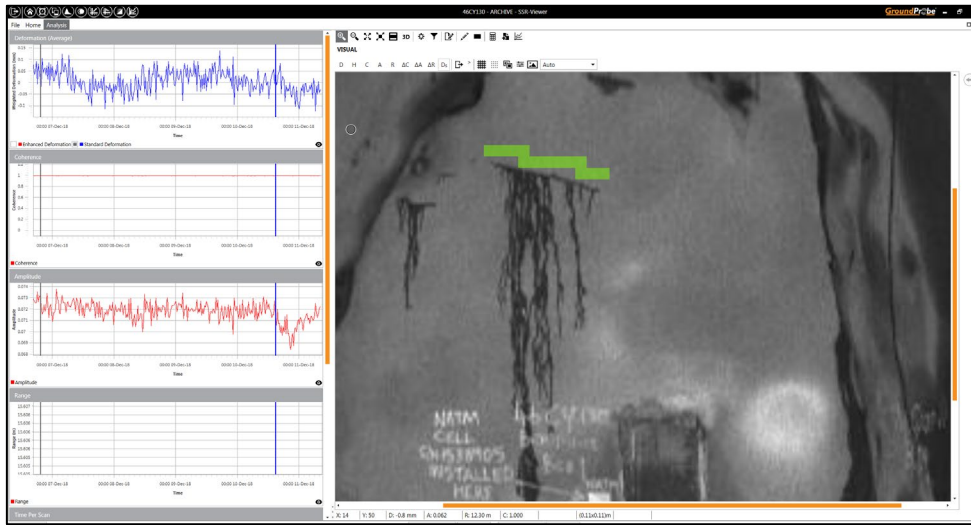
Figure 10 Displacement plot of selected pixels adjacent to apparent tension crack shows no indication of either positive or negative deflection/displacement suggesting these structures did not occur as a result of any static load caused by the fill behind.

The peak pressure measured by the sensor installed behind the Cyan 130 barricade reached only 119 kPa during the Plug Pour. This pressure decreased, as expected, shortly after Plug Cure begins and continued to decrease during the Body Pour, decreasing to background levels shortly after.
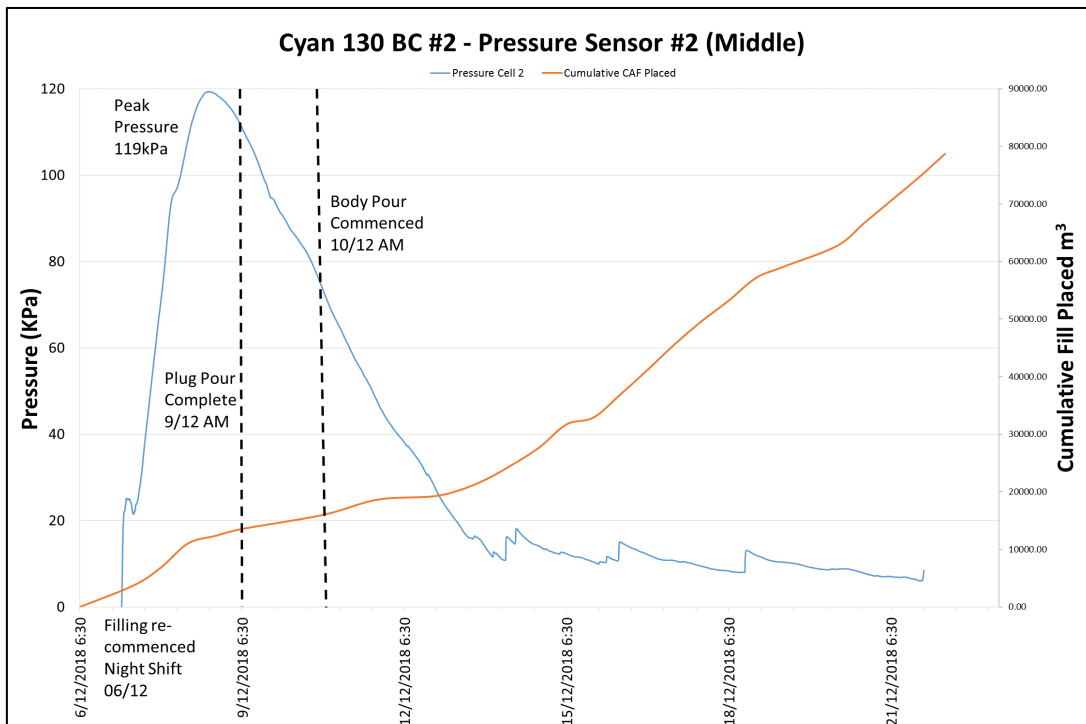

Figure 11 Pressure monitoring results for instrumented Cyan 130 barricade

6   Concluding Remarks

Initial testing of the new fill strategy, as described in this paper, has demonstrated the opportunity to decrease stope fill time by up to 20% compared with the previous fill strategy. This change will enable stopes to be turned over faster, allowing faster re-entry to new stoping areas, hence facilitating future business requirements for Olympic Dam mine.

The GroundProbe GML system was tested as a proof of concept exercise to demonstrate the ability to accurately monitor for any potential deflection/deformation of a shotcrete barricade during implementation of the new fill strategy. It was demonstrated that it is possible to monitor remotely for surface deflection with sub-millimetre accuracy, in near real-time with the scanner operating autonomously, scanning continuously over time. Although this project involved testing at just one test location, it presents a potential additional opportunity to optimise processes even further.   For example, it may suggest an opportunity for future test work to assess the risk and controls required to remove the curing period for the initial Plug Pour or test the other restrictions on fill rate to further speed up the back-filling process.

The GML measured no deformation of the Cyan 130 barricade, which supports previous non-linear numerical modelling results. Although this was a single test and in no way can be used to set a precedent for future application, it demonstrated the applicability of the GML system for monitoring of shotcrete barricades and the apparent opportunity to test what may be considered overly conservative restrictions on filling rates with displacement monitoring applied as a risk mitigating control.

7   Acknowledgement

8   References

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