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Implementing a stability monitoring system at a legacy mine site—case study

O Gibbons *SRK Consulting Inc., Canada*

AG Hartzenberg *SRK Consulting Inc., Canada*

A Joaquim *SRK Consulting Inc., Canada*

T Coleman *SRK Consulting Inc., Canada*

Abstract

Canada has a rich history of mining that has played a significant role in shaping Canada's economy and development. Mining has also left a lasting legacy in the form of closed or abandoned mines. These mine sites often pose safety risks, specifically related to the stability of historical open pit and underground workings—their closure and remediation present significant challenges. This paper discusses a legacy mine site case study focusing on the implementation of a suitable rock mass stability monitoring system.

The legacy mine site is located within the town boundaries of a community in northern Canada. The site includes an interconnected open pit and underground workings where some of the mine workings were backfilled. Based on available information, the mine was closed after a failure occurred at depth and some backfill material was lost to a deeper section of the mine. A pond currently exists where the open pit was located.

This paper includes a detailed discussion of the existing instrumentation and the implementation of a more comprehensive stability monitoring strategy. The stability in this case is of particular importance, as the site is close to community infrastructure, and consequently, community residents. This paper addresses the benefits of the selected monitoring system and each system component, and includes the challenges resulting from the geographical location, rock mass conditions, and maintenance due to the remoteness of the site. There were no local employees available to address the monitoring system health.

The site has not experienced any documented instability since the mine had closed, based on almost three decades of shallow monitoring and site observations. The installation of monitoring systems is usually, targeted at monitoring movement. However, for this site, instability and ground movement were not expected, leading to monitoring focusing on system health and the detection of potential movement. The lack of employees on site also made the health and functionality of the monitoring system critical as there was a desire to prevent frequent system maintenance and troubleshooting.

Keywords: *mine closure, instrumentation, rock mass stability, mine monitoring*

1 Introduction

The rich mining history of Canada has led to the occurrence of multiple legacy mine sites that can pose safety risks to communities. Adhering to the mine closure regulations can aid in mitigating these risks through appropriate mine closure strategies. In this case, an integrated monitoring system was designed and installed to leverage various monitoring instruments to cover the areal and depth extents of the mine workings. Real-time monitoring was particularly important due to the location of the legacy site within the town boundaries of a mining community in northern Canada.

While the mine was operational, gold and silver were being mined from narrow quartz veins using both open pit and underground methods. Currently, the mine site includes an interconnected open pit and underground workings that are filled with water. A pond currently exists where the open pit was located, which has now been filled with water. Some of the mine workings were backfilled but detailed bathymetric and three-dimensional sonar surveys (grey shapes in Figure 1) of the workings showed that some of the backfill was lost to deeper mine workings. It is believed that a ground failure at depth may have caused this to occur.

Figure 1 shows the near-vertical open historical mine workings (grey hatched areas). The dimensions include a strike length of approximately 220 m, width of 35 m, and depth of 115 m. The focus of monitoring is on the hangingwall (HW) and footwall (FW) of the workings, with minimal concern over the stability of the ends of the workings. An area of potential instability had previously been identified, and monitoring instruments were installed at shallow depths along the HW side to cover this area. There is also a thin crown pillar within this area that covers approximately half of the length of the workings. The stability of the crown pillar was of particular concern during the geotechnical stability studies (Joaquim et al. 2021), (Hartzenberg et al. 2021) as people were working in the area. In monitoring the site, the stability of the crown pillar is of concern as it is one indicator of overall stability of the opening.

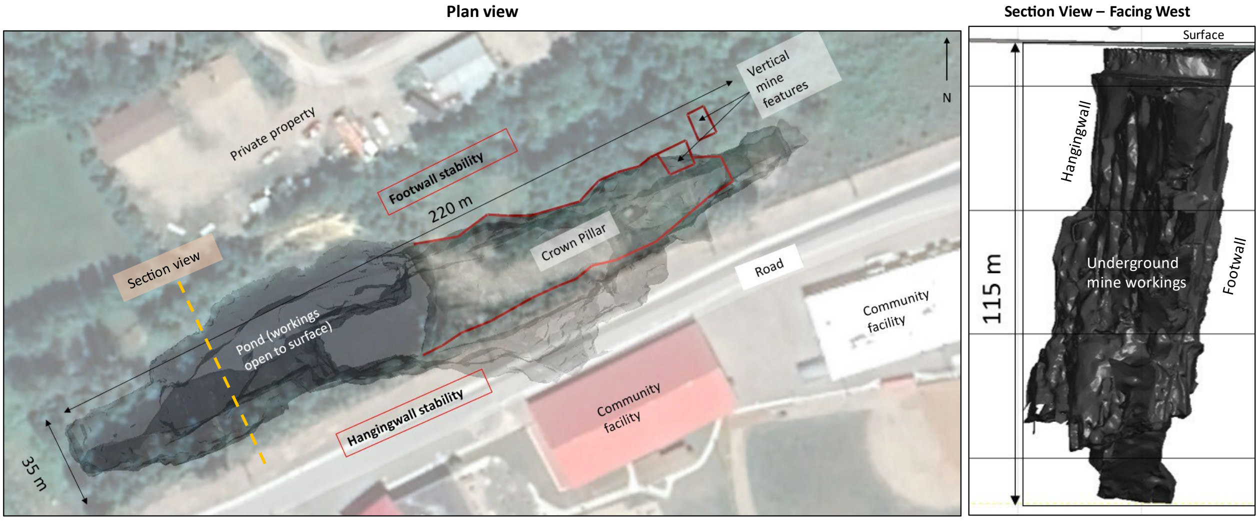

Figure 1 (left) Plan view of the mine site, showing the mine workings (grey shapes) in close proximity to a residential community; (right) section view from the surface extending to depth, showing the HW and FW side of the near-vertical mine workings

The site has not experienced any documented instability since the mine had closed, based on almost three decades of shallow monitoring and site observations. Usually, instrumentation is targeted at monitoring movement. In this case, instability and ground movement are not expected, leading to monitoring focusing on system health (such as instrument robustness, power, and data upload reliability) in addition to the typical detection of possible movement through instrumentation. The lack of employees on site also makes the health and functionality of the monitoring system critical to prevent frequent system maintenance and troubleshooting.

2 Methodology

The approach for selecting a stability monitoring strategy for this site was designed to allow for real-time monitoring of an area of potential instability surrounding the mine workings. The system was also designed with consideration of unique challenges specific to the site being a legacy site and its location within a northern residential community. The challenges considered when developing the monitoring system and the proposed solutions to mitigate these challenges are summarized in Table 1.

Table 1 Monitoring challenges and proposed mitigation strategies considered for selecting a stability monitoring strategy

Monitoring challenge	Proposed mitigation strategies
Potential ground movement	Monitoring covering near-surface and full depth of open historical workings on HW & FW
No availability of utilities on site (e.g., power and communication)	Cellular communication for monitoring stations and solar panel and battery back-up operator systems
No personnel on site	Simple & robust system and instrumentation overlap between areas of concern
Uncertainty in applicability of nano seismic system	Phased approach to the system implementation to assess the applicability prior to installation
Accommodating location of the mine workings within a residential community	Daytime drilling only (noise), strategic placement of drillhole collar locations to minimize impact on town activities, and cables from monitoring devices should be routed to monitoring stations, ensuring minimal visual impact to the surrounding areas

Considering the potential challenges and mitigation strategies, the detailed monitoring implementation plan was executed. The specifics of the detailed monitoring implementation plan are shown in Figure 2, and presented below:

- Time domain reflectometry cables (TDRs) were installed previously in historical drillholes for shallow monitoring purposes along the HW. Eight of these TDRs that could be located were reconnected to the current monitoring system.
- A total of 18 drillholes were completed between 2019 and 2021 around the underground mine workings at different orientations and depths to optimize coverage of the area. Most of the monitoring instruments were designed to be installed in these diamond drillholes around the site.
- The monitoring system consisted of a number of instruments including:
    - Two ShapeArray instruments – installed along the HW and FW for near-surface monitoring along the majority of the strike length of the open pit pond.
    - Sixteen TDR cables – installed in 16 drillholes to monitor stability along the entire length of each drillhole. This monitoring covered different locations and depths along the workings.
    - Three vibrating wire piezometers (VWPs) – monitoring the water levels. VWPs were installed in selected drillholes that intersected the underground workings filled with water.

A phased approach was considered for the nano seismic monitoring system. Before considering installing a permanent array of geophones in drillholes around the site, a feasibility study was proposed with a small temporary array deployed on the eastern side of the pond. Phase 1 included drop tests on the ground surface and into the water-filled workings to give a better indication of the local conditions. With the success of Phase 1, Phase 2 included the installation of downhole sensors. These techniques detect the extremely low-energy signals produced by cavitation in unconsolidated material. The nano seismic system was installed in selected drillholes.

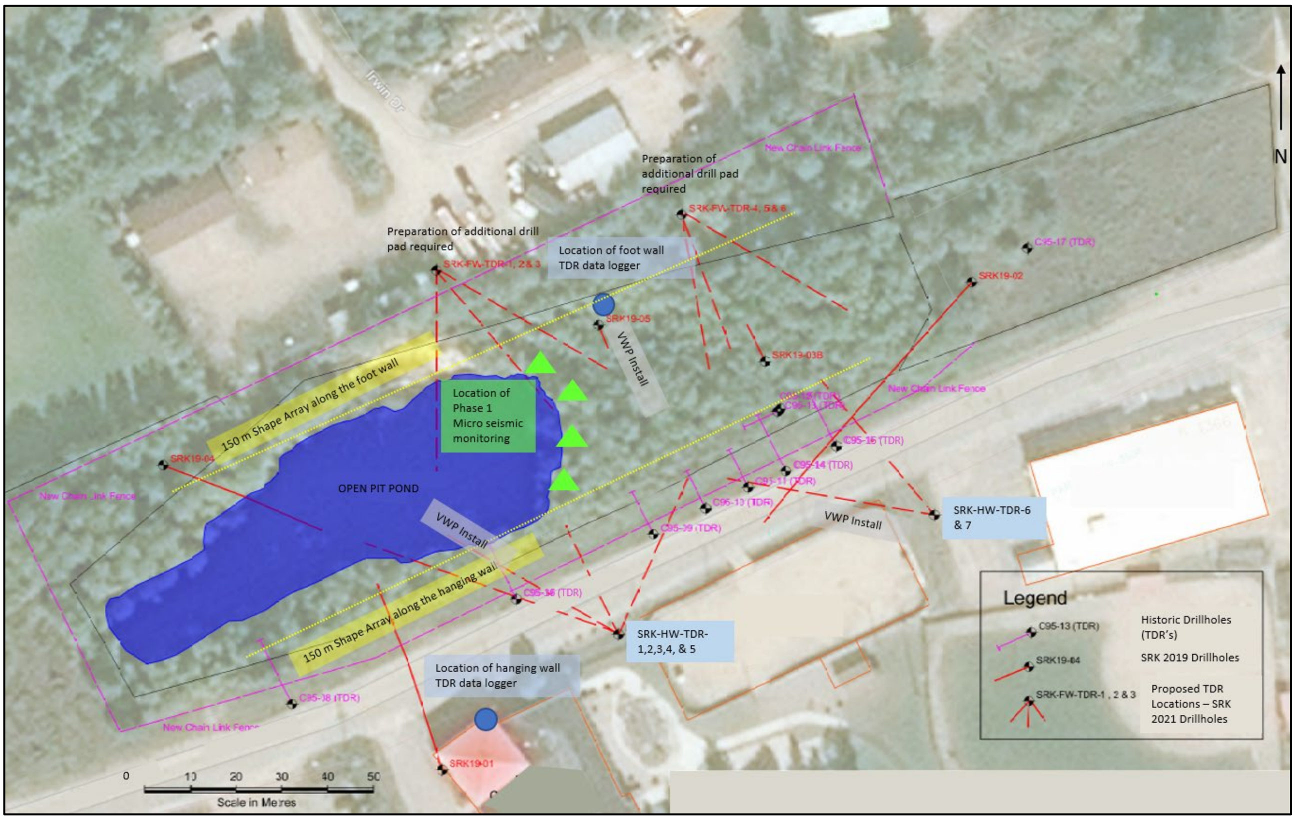

Figure 2 Plan view of the detailed monitoring implementation plan

Multiple aspects for the planning and execution methods of the monitoring plan were considered. The main challenge was the location of the site within a town setting. Drillhole collars would have ideally been all within the site property limits; however, to obtain appropriate coverage of the underground workings, some drillholes had to be collared on private property and on community facility property. Care was taken during drill transportation to avoid damaging community roads. Scheduling for the drilling also involved consideration of the seasonal use of some of the community facilities, and was planned to be performed during off-peak utilization of the facilities. Drilling also only took place during the daytime to avoid disturbing the community at night.

The challenge with a legacy mine site is that no larger mine site system exists to utilize for power and communications. The site was also not tied into the residential utilities. Therefore, alternative sources, including batteries and solar panels were utilized to provide power to the monitoring system. Data loggers recorded data from the TDRs, VWPs as well as the nano seismic system. Cellular modems were connected to the data loggers to communicate with the regional tele-communications system to transfer the data to a remote server. The monitoring system also had to be simple and robust as there are no full-time personnel stationed at the site, making it cumbersome and expensive to investigate or fix system malfunctions easily, or in a timely manner.

Overlap in instrumentation coverage areas and segmentation of the power and communication systems was planned into the monitoring strategy to increase system robustness. This was deemed important in case of malfunction of the instruments, data loggers, power sources, or communication. The instruments were also planned to communicate in real time. These aspects were of particular importance as the site is within the boundaries of a residential area, so dependability of the system, as well as quick response times, were crucial.

It was important for the monitoring system to be secure so that it would be difficult to damage by accident with the local town people frequenting the vicinity of the site. As much as practical, equipment was stored within the fenced site area. However, some drillhole collars, cables, and data loggers had to be placed outside of the fenced site area. In this case, drillholes were capped, cables were buried to avoid damage, and data loggers were placed within enclosed, secure structures.

Once the drilling and monitoring system installation was complete, care was taken to restore any disturbed areas by patching pavement and seeding areas where trenching had been necessary to bury cables. This was done to minimize the visual impact of the monitoring system on the community.

3 Implementation

The methodology for the implementation of the monitoring system considered the potential unknowns. The main components of the implementation phase included:

- Review of three-dimensional bathymetric and sonar surveys to plan drillholes for maximum coverage around the mine workings along full depth of void. Planning of the placement depths of monitoring devices downhole in the drillholes.
- Planning of the trenches' locations for the ShapeArray instruments.
- Adjustments to the planned drillhole collars in the field.
- Consideration of utilities (e.g., required distance of drilling from overhanging powerlines, underground water pipes, etc.)
- Water sources for drilling (offsite water source or water from the open pit pond).
- Geotechnical data collection during the drilling phase.
- Installation of Van Ruth Plugs in drillholes drilled into the underground workings prior to the installation of monitoring devices.
- Execution of the monitoring placement plan, installing TDRs, VWPs and nano seismic monitoring devices in assigned drillholes, ShapeArray instruments in trenches, as well as the installation of data loggers and solar panels.
- Grouting of drillholes to surface elevation (grout visible at the collar of each drillhole).
- Directing the cables connected to each monitoring device on surface to the connection at the data loggers.
- Setting up of the data loggers, including the connection of all monitoring devices, cellular communication connections as well as the battery, and solar panel set up.
- Communication with each monitoring device service provider to ensure each device was functional.

It is important to note that there were aspects of the drilling and instrumentation that had uncertainty worked into the plan. Additional unexpected unknowns and challenges were identified during the implementation phase. The phases of the monitoring plan implementation, including challenges and potential solutions will be discussed in sections 3.1 to 3.5.

3.1 Drilling and grouting

Drilling commenced in the fall of 2021, collecting geotechnical data for rock mass characterization and stability analysis. Some drillholes unexpectedly broke through into the underground workings and required the installation of Van Ruth Plugs, prior to instrumentation installation and grouting.

The drilling phase was completed with minimal delays; however, multiple challenges were encountered during the grouting phase. Grouting first commenced in the fall of 2021. The grouting was initially planned to take place before winter fully set in due to the northern site location and expected delays associated with wintertime grouting in extreme winter conditions. However, due to unexpected delays, the grouting program commenced later in the fall and extended into the winter. Grouting rates became much lower than would have been expected in a northern Canadian climate.

Portland cement was originally used for the grouting, and in some cases, significant grout losses were experienced. It is believed that this could have been as a result of extreme cold weather conditions and / or the occurrence of underground features. These features might include geologic structures and blasting fractures exposed along the drillholes and also identified during geotechnical data collection. Grouting was originally done with the drill rig, and a combination of bentonite chips and AMC Gel (Bentonite) were used to try and mitigate the grout losses. Due to the delays experienced, it was decided that a Water Cut Off grout should be used, and a grouting crew and an additional grout pump were brought to site by the contractor to continue with the grouting. Grouting was performed using the diamond drill.

As a result of the very low grouting rates, a decision was made to stop grouting for the 2021 winter season and to return to the site in 2022. The drillhole collars on the FW side could remain open; however, the drillhole collars located on the HW side in between community facility buildings had to be filled on request of the community. In anticipation of having to locate the collars for the 2022 spring season, a local carpenter created wooden boxes that were placed over the collars and the areas were filled in with mostly sand material or cold mix asphalt, as seen in Figure 3.

Drillhole collar with installed instrumentation covered in wood enclosure

Drillhole collars located close to community facilities. Installed monitoring devices with drillhole collars covered with wood enclosure

Figure 3 Drillhole collars at the end of the 2021 field season; wood enclosures were created to cover the drillhole collars in order to locate them during the 2022 field season

Grouting resumed in the spring of 2022, when a contractor used a grout plant rather than a drill rig for grouting purposes. Due to the significant grout losses experienced during the 2021 season, the grout supplier suggested the use of grout socks to mitigate these challenges.

Figure 4 shows the grout socks that were used during the 2022 season. The grout socks were used in highly fragmented rock mass. A poly-cotton mix textile that had low permeability, but high elasticity was used for the manufacturing of the grout sock. In the process of the sock being filled with grout, the solid particles clogged within the sock and filled the drillhole. The cementitious water that filtered through the grout sock cemented the mass to the inside of the drillhole. Grout socks were supplied in rolls and were cut to lengths chosen during installation.

Figure 4 (left) Grout sock secured around PVC pipe prior to installation in the drillhole; (right) lowering the PVC pipe and grout sock into the drillhole for grouting

The grouting process was still time consuming, even with the use of grout socks. At the start of the 2022 field season, grout socks were only used where challenges were experienced in grouting, and grout gain would often be approximately the length of the grout sock used in the drillhole. By the end of the season, long grout socks were used to complete the program within the planned 2022 schedule. Grout socks were found to be more effective than G-Stop, bentonite chips, or bentonite pellets in this setting.

Another strategy that was used to reduce grout loss was the reduction of batch sizes and allowing for some time between the batches, providing increased time for the grout to set. In a typical rock mass, grout that enters features could seal them, allowing for improved grout gains with the follow-up batches. In this setting, it is believed that grout was pushed through the fractures into the workings and was thus lost more readily than in other environments. Smaller batches of higher density grout were found to be more effective in this setting, especially in getting past specific features in the drillholes.

Difficulties were also experienced with grout set times being much longer than those specified by the grout manufacturer. The supplier provided a 30-minute Water Cut Off grout. It was found that in the field, the grout took approximately six hours to set—a specific cause could not be identified. A combination of using the Water Cut Off grout together with the grout socks proved to be successful with completing the grouting of all the drillholes to surface.

3.2 Historical TDR cables

Historically TDR cables were installed in 1995 and have been monitored from 1997 to 2018. The latest 2018 report indicated that there were nine existing, functional TDR cables on site and that the waveforms of these cables were stable when compared across the years since installation. Therefore, movement indicative of failure had not been registered on these TDR cables.

The challenge identified with these TDRs is that some cables were not clearly marked and buried under topsoil. Areas on the site were excavated to try and locate all of these TDRs in order connect them to the new data loggers in order to record data in real time. Unfortunately, two of the TDRs could not be located, although one TDR cable was found that had not been included in the original plan for connection to real-time monitoring.

The eight TDR cables located to the south of the workings were spliced to additional cable lengths and these new cable lengths were buried in trenches approximately 1 ft deep. A GPS location was recorded for each TDR collar. The TDR cables were placed in 1 inch PVC pipes and directed to a data logger so that they can be continuously monitored.

3.3 ShapeArray instruments

Two 150 m long ShapeArray instruments were installed on the HW side (Southern ShapeArray) and FW side (Northern ShapeArray) of the historical mine, parallel to the strike direction of the underground mine workings. Trenches were excavated and the ShapeArray instruments were installed along these trenches using specifications provided by the manufacturer. The extension cable for the ShapeArray instruments were connected to the data loggers. GPS locations were collected along both ShapeArray instruments to document the exact location of the instrumentation for record keeping purposes.

3.4 Nano seismic system

A two-phased approach was used to optimize the installation of the nano seismic system.

Phase 1 consisted of creating a temporary installation of geophones and performing drop tests (dropping boulders with an excavator on the ground surface and in the pond). The main objective of the experiment was to provide some estimate of the level of sensitivity that could be achieved with the future permanent array. To determine this, several drop tests were undertaken at different distances from the monitoring area. The findings from Phase 1 indicated that the already planned geotechnical drillholes could be used for the geophone installations to successfully implement Phase 2.

Phase 2 was planned based on the results from Phase 1. Uniaxial and triaxial geophones were installed at 30 m and/or 50 m depth in the drillholes. A FW and HW data logger station was installed for data collection. The data collected is currently recorded and reported on a monthly basis to primarily monitor backfill stability as well as the system health.

3.5 Time domain reflectometry and vibrating wire piezometers (VWPs)

Sixteen TDRs and three VWPs were installed in the drillholes completed during the field program as shown in Figure 5. All instrumentation were connected to assigned data loggers along the HW and FW of the mine.

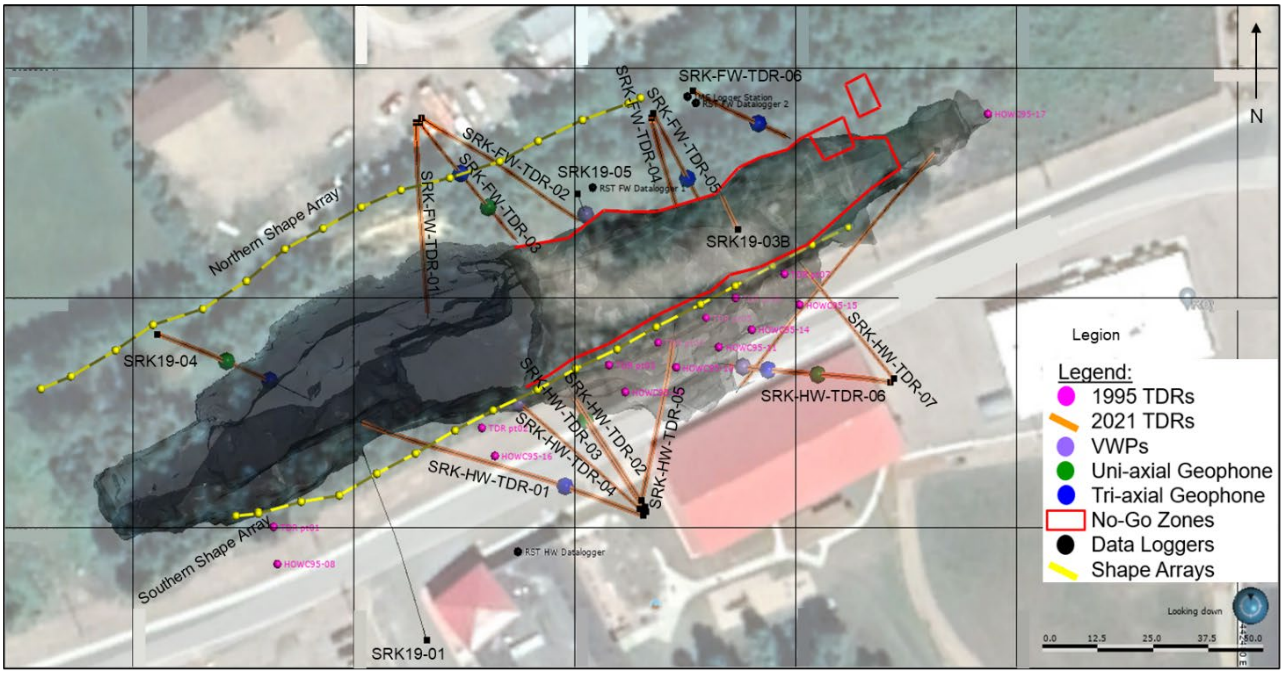

Figure 5 Plan view of the post implementation detailed monitoring plan

Figure 6 shows two section views along the historical underground mine workings (grey hatched area), together with the drillholes completed, and types of monitoring instrumentation installed during the 2021 field season. These sections show significant coverage around the historical mine workings, also monitoring at shallow elevations and at depth.

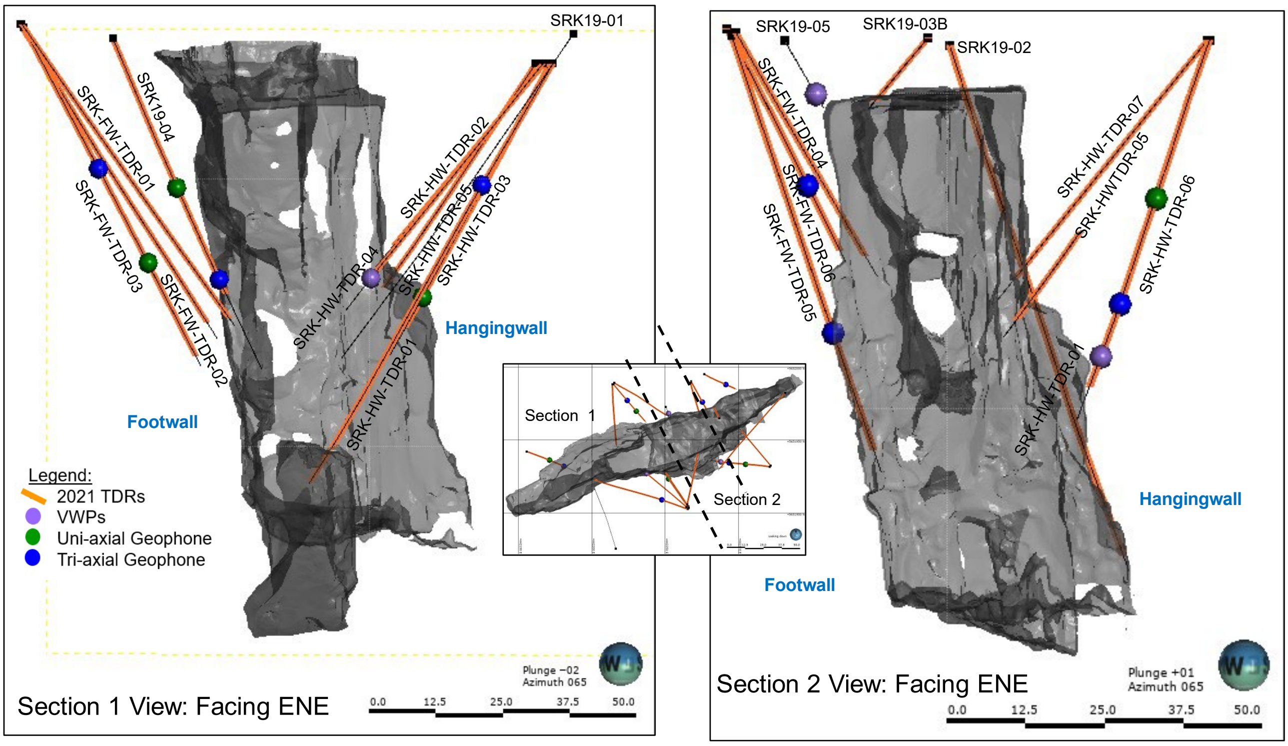

Figure 6 Section views showing the installation of multiple monitoring systems along the HW and FW of the historical mine workings at shallow elevations and at depth

4 Results

One year following the completion of the installation of the monitoring system, it is functional. Various elements of the system have experienced problems, and this reinforces the benefits of the strategy for the system to have overlap in instrument coverage.

The solar panels have been replaced with larger panels, but power supply outages persist in the winter months. System health is being closely monitored, alongside ground movement.

The nano seismic system is very unconventional compared to those installed in operating mines. Usually, these systems are designed to measure seismic activity associated with ground movement at a mine site with active mining induced seismicity. However, the expectation for this site is that rock mass movement does not occur, and seismic activity is thus not triggered. This system has been implemented to primarily monitor the potential of movement of the backfill material. In the case that the backfill material mobilises, it might result in a decrease in confinement and then the rock mass would be more susceptible to instability. As a result, changes to the way data was reported was required to best suit this unique site.

Nano seismic data is being reviewed monthly, with a report summarizing the data being compiled on the same frequency. System health monitoring is a large component of the monitoring as personnel are not reviewing the data daily and triggers or alarms have not been set up. This is different from an operating mine where a seismic system would be closely monitored. The nano seismic system is recording very small amplitudes, mostly below 0.2–0.3 mm/s. Ambient noise has been observed to be low during winter months, with ground motion amplitudes barely reaching 0.001 mm/s. Ground motion variability between night and day have been picked up by the nano seismic system. These are of very low orders (1e–3 mm/s). This indicates that there are no significant changes in the noise conditions that might have been produced by any sources outside of the common ones, such as wind, water, or traffic. This is also unique to the calibration of the system having been aligned to a legacy site.

Based on the data collected and the regular wintertime power loss, reporting was adjusted to show the triggered section of each individual station. This, together with the system health, was believed to give a better idea of what was happening at each monitoring station. The intent was to try to isolate stations that were not operational and give a better idea of the data collected within the operational stations. Based on the lessons learned, additional monthly analyses were added, including 'Measured Ground Motions' and a comparison of 'PGV (peak ground vibration) vs Corner Frequency (dominant frequency in Hz)' to aid in potential correlation of distant blasts from mines within the mining district, and ambient noise.

Variability in ambient noise was measured to be mostly stable, with variations mainly being attributed to daily anthropogenic activities.

The TDR system includes 16 new TDRs and eight historical TDRs. Of the new TDRs, three appear to be damaged based on the waveform shapes, with possible causes including water ingress or a short circuit (Figure 7). Reliability in communication has also been an intermittent issue. The reception from the surrounding cell towers appears to be poor at the data logger locations. Antennae have been moved to try to point as directly as possible to the closest tower, but communication is still lost intermittently.

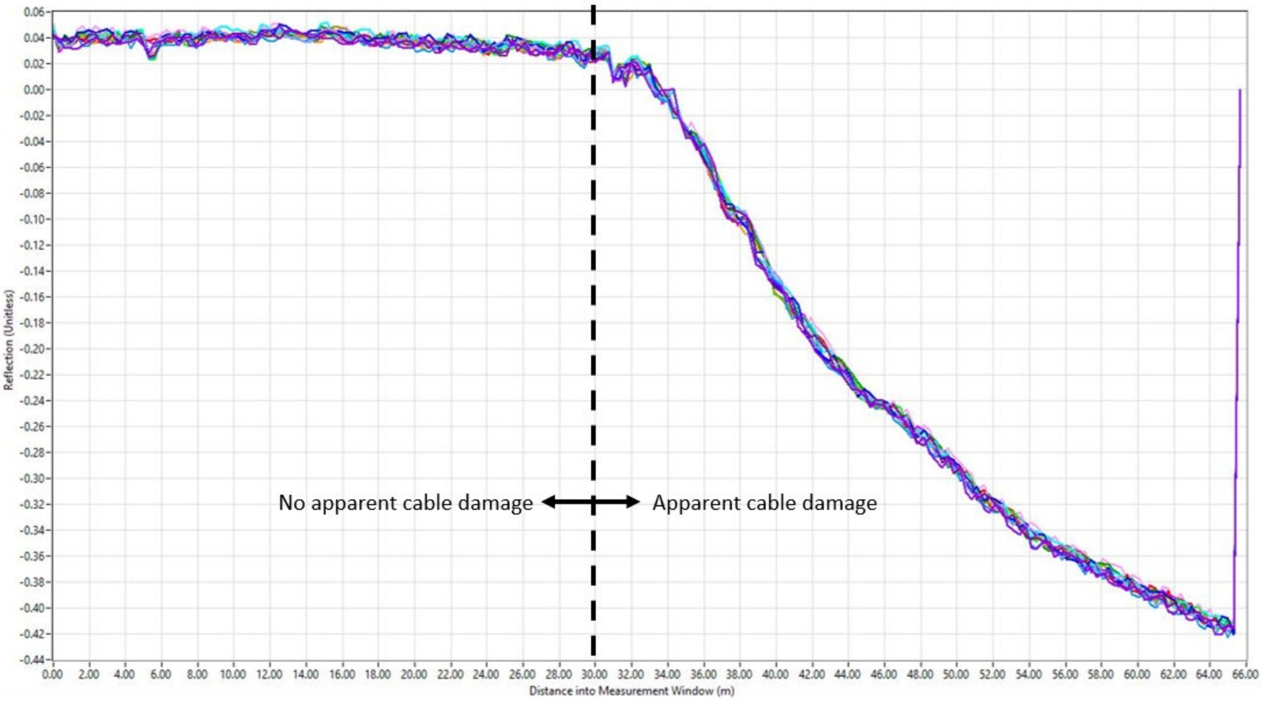

Figure 7 **Example of TDR data with possible water ingress or a short circuit around 30 m distance along the cable**

The two ShapeArray instruments have been fully functional since installation. Measurements showed initial movement and heave, followed by subsequent settlement as the site normalized to equilibrium after the first freeze-thaw cycle (Figure 8). The data suggests that the instruments were nearing equilibrium around half a year following the installation, with settlement to statis following this period. The most recent half year shows the system being mostly static.

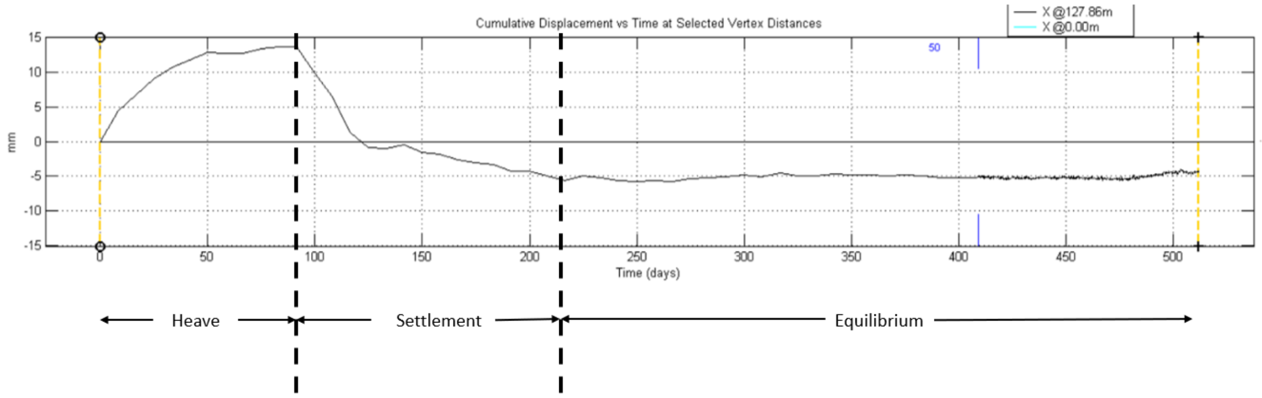

Figure 8 **ShapeArray data showing initial heave, followed by settlement and nearing equilibrium at approximately 200 days following installation**

5 Conclusion

The detailed monitoring plan was completed during the 2021 and 2022 field season. Extensive planning was conducted prior to the program but fit-for-purpose adjustments during the implementation phase were required, based on unexpected challenges with instrumentation installation and grouting that is discussed in this paper. Implementing strategies commonly used on active sites and re-fitting their purpose for site-specific needs of a legacy property played a vital role in the execution of this project, including reporting on the health of the different monitoring systems. A combination of monitoring systems was installed to address the project specific needs.

Acknowledgement

A word of thanks to all parties involved in the successful implementation of the monitoring program, including the drilling company, contractors, equipment manufacturers, and the owner of the property.

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