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Novel approaches of geotechnical investigation for mine closure projects in Canada

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Abstract

Innovative data acquisition and ground monitoring approaches are now being used to support the decommissioning and reclamation of the various types of excavations found at mine sites. Remote data acquisition and visualization technologies have improved the ability to gain a spatial understanding of mine excavations and structures as well as the quality of the surrounding rock mass. These technologies have led to greater confidence and reliability in the outcome of mine closure designs by enabling advanced engineering analyses and increasing personnel safety.

To ensure the safety of the public and allow for productive use of the land after the mine is closed, geotechnical assessments are conducted to evaluate the longer-term stability of open pit and underground mine excavations. The acquisition of data to support these studies can be challenging particularly for historic or legacy mine sites where there is limited availability of design and implementation records and inspection reports on the state of excavations post mining. These excavations can also be difficult to access safely because of rock mass damage caused by instability surrounding these structures. The installation of ground monitoring methods can also be challenging due to the instability that occurs post-mining.

The technologies and monitoring methods discussed in this paper include photogrammetry, slope inclinometers (SI), time domain reflectometry (TDR), bathymetric and sonar surveys, terrestrial, Light Detection and Ranging (LiDAR), and Interferometric Synthetic Aperture Radar (InSAR). Example uses of these technologies and surveying methods in various mine closure projects are reviewed including advantages and limitations of each technique mentioned above. Assessing the usage and execution of these techniques can determine which methods are appropriate for use in other projects.

Keywords: *open pit, underground excavations, remote data acquisition, monitoring methods, geotechnical stability*

1 Introduction

The crucial role of the mining industry in the global economy is undeniable, however it can have considerable impacts on the environment and society if not carried out responsibly. To ensure that this industry operates in agreement with social well-being and minimize environmental impacts, developing a mine closure plan for an operation is a key part. To have a well-defined mine closure plan, acquiring accurate and reliable geotechnical data is fundamental and heavily dependent on choosing the right data collection methods. Robust data collection ensures transparency, enables effective monitoring, and can be used effectively in multiple areas such as environmental impact assessment (Hanich, et al., 2014), social and economic considerations (Mallikarjun Rao & Pathak, 2005), and soil and rock stability (O'Connor, 1994).

The process of geotechnical data collection in the past has relied on visual inspections and reviewing the available data such as old plans and construction drawings, mine reports, and conversations with mine personnel. Additionally, drilling campaigns or review of existing core, and structural mapping were part of data collection process. In certain situations where accessing remote areas of underground mines was challenging, remote techniques were employed to identify underground cavities that previously were unknown. These techniques included geophysical methods, ground penetration radar, microgravity, seismic cavity resonance, and microwave radiometric surveys (Hutchinson, et al., 2002).

With the recent advances in technology, the way data is collected has been improved in the mining sector and consequently in mine closure planning. These innovations, result in more accurate and comprehensive information that is captured in a safer and cost-effective manner (van der Merwe & Andersen, 2013); (Kumar Singh, et al., 2023). This is particularly advantageous for mine closure projects with limited budgets, as it allows for efficient utilization of resources. This paper discusses case studies that have utilized various data collection techniques in mine excavation closure planning. Specifically, it focuses on the implementation of borehole camera, slope inclinometer (SI), time domain reflectometry (TDR), photogrammetry, light detection and ranging (LiDAR), cavity laser scan, and interferometric synthetic aperture radar (InSAR) methods. By utilizing these technologies, mine closure projects can optimize their budgets by focusing resources on targeted areas that require attention, helping to ensure effective and environmentally sound closure of mining operations.

2 Technology

The accessibility and application of technology used in mine closure projects has significantly increased, making it more feasible to implement these tools even for projects with limited budgets, such as mine closure initiatives. Advancements in technology have led to the development of cost-effective solutions that can provide valuable data and aid in the closure process. For example, remote sensing technologies, such as drones equipped with high-resolution camera or LiDAR sensors have become more affordable and accessible. Remote data acquisition plays a significant role in mine closure projects for several reasons including the following:

- Safety: Mine closure activities often involve hazardous environments, including unstable areas/structures, contaminated areas, or inaccessible terrain. Remote data acquisition allows for monitoring and data collection without exposing personnel to unnecessary risks. It minimizes the need for physical presence in potentially dangerous locations, ensuring the safety of personnel involved in the closure projects.
- Cost Efficiency: Mine closure projects can span large areas, and frequent on-site visits for data collection and monitoring can be costly, especially if the mine site is remote or difficult to access. Remote data acquisition eliminates or reduces the need for frequent travel and site visits.
- Data Management and Analysis: Remote data acquisition often involves the integration of data management and analysis platforms. These platforms can store and process data, allowing for efficient data management, trend analysis, and reporting. It facilitates the extraction of valuable insights and supports informed decision-making during the mine closure process.

Remote data acquisition in mine closure offers significant benefits, including improved safety, cost savings, real-time monitoring, and efficient data management in mine closure projects. Remote monitoring also offers several benefits in terms of cost reduction such as reducing the need for frequent on-site visits by experts and alerts can ensure experts are notified only when necessary. Additionally, data provided using these methods are auditable and helps strengthen compliance in mine closure projects.

The advantages, limitations, and considerations of each technique, as identified through the case studies, are presented in Table 1 and Table 2.

Table 1 Technologies used in mine closure initiatives advantages and limitations

Data aquistion method	Purpose	Advantages	Disadvantages
Time domain reflectometry (case study 1 & 2)	Early change detection and monitoring of open pit, underground, and crown pillar stability, used in combination with other methods to obtain a comprehensive understanding of slope behaviour	Relatively low cost compared to slope inclinometers, long-term data collection, monitor potential ground displacements before they appear at surface, and identify location of the failure surface	Data does not show direction and magnitude of movement, limited spatial coverage, sensitivity to cable placement in the exact location and orientation, and additional cost for personnel required for monitoring
Slope inclinometer (case study 1)	Early change detection and monitoring of open pit, underground, and crown pillar stability, identifying depth to failure surface, and displacement data used to compare and calibrate numerical model inputs	Long-term data collection and applicable to most slope monitoring scenarios to assess ground movement	Limited spatial coverage, requires regular maintenance to ensure accurate measurements, and additional cost for personnel required for collecting data and monitoring
Photogrammetry (case study 2)	Digital mapping of structural features exposed in open pit and underground excavations, tracking changes on the area of study and open in different time periods to locate failure risks in open pit, and provide detailed and accurate documentation of the excavation condition	Data collection from safe distance with ability to collect remotely (e.g., drone) and rapid cost-effective data collection with highly detailed 3D model	Density and accuracy of point cloud data depends on image resolution and quality, requires precise image acquisition and calibration, extensive data processing required to create useful photogrammetry model, cannot capture internal structures or hidden features, and physical characteristics of structures can't be measured
Bathymetry survey (case study 3)	Define flooded open pit and underground excavation extents, characterize distance to existing backfill in flooded open pit and underground excavations	Eliminates need for divers to physically enter flooded excavation, compact and easily navigable, accurate water depth measurement	Dependant on water clarity; reduced accuracy in sediment-laden waters, requires platform such as boat/aircraft; cannot navigate in confined spaces, and requires minimum depth of water
Cavity laser scan (case study 2)	Used to define the location, size and shape of the underground void that is inaccessible	Can provide accurate and detailed point cloud for model development and is an efficient data acquisition technique	Processing the data can be complex, limitations in wet conditions, survey requires direct line of sight

Table 2 Technologies used in mine closure initiatives advantages and limitations

Data aquistion method	Purpose	Advantages	Disadvantages
3D sonar survey (case study 3)	Safety and stability assessments, defining flooded open pit and underground excavation extents	Eliminates human exposure, high density/high-quality data of underwater topography, excavation dimensions and submerged structures, and surveys cover large areas efficiently with ability to review results in real time	Time consuming data processing/ interpretation, limited area coverage for single survey; can require multiple surveys to capture site environmental constraints; limited by water availability and hazardous substances, and extensive data processing required to create useful 3D model
Borehole camera (case study 2)	Visual inspection of excavations and cavities, locating specific access points and entryways, and to identify the presence of backfill in the underground excavations	Relatively low cost, provides live visual feedback, able to record videos or capture images	Image/video quality is highly dependent on lighting, dust, and water flow, results are restricted by field of view and limited visibility range
InSAR (case study 1)	Used for historic change detection and monitoring of collapses, subsidence, and other ground deformation issues	Capable of retrospective monitoring (analysis of historical data), operable in clouds/haze and darkness, and is cost-effective for long-term monitoring of large areas	Vegetation interference, lower resolution. compared to LiDAR, radar coherence may be compromised in areas with loose material, data gaps can occur if displacement occurs out of the line of sight and requires additional techniques
LiDAR (case study 1 & 2)	Establish baseline conditions and change detection models, inspection of shafts and detecting areas of stability concern along the shafts	High coverage and spatial resolution, high-density point cloud with accurate elevation measurements, and highly effective for change detection and monitoring for the purpose of surface deformation analysis	Time-consuming data processing, expensive when covering large areas/repeating surveys overtime, scan can be disrupted by heavy rain or cloud coverage, spatial resolution and positional uncertainty vary depending on scanning systems and processing algorithms

3 Case studies

3.1 Case study 1

This case study includes a pit stability assessment conducted at the Faro Mine Complex in Yukon Territory, Canada, and highlights the key geotechnical aspects that need to be considered when conducting thorough open pit stability assessments during mine closure in weak rock formations. One of the primary objectives was to evaluate two areas of instability that exhibited slow creep, regression and erosion during operation and continued post-mining. The case study outline is shown in Figure 1a and InSAR results are show in Figure 1b.

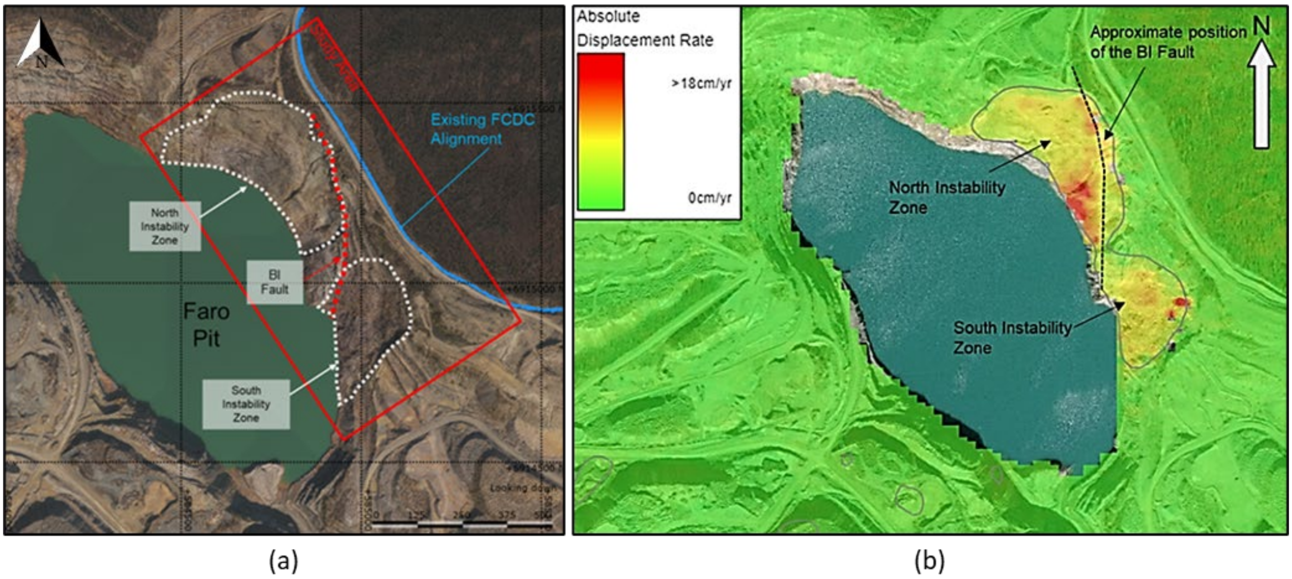

Figure 1 Study area (a) general outline (b) InSAR results (Saunders & LeRiche, 2021)

The focus is on the slope stability assessment to determine an appropriate positioning of a new permanent non-contact water diversion channel, ensuring it is located outside the projected long-term pit slope break-back. The stability analyses required a thorough geotechnical investigation to understand the slope failure mechanism. The investigation consisted of using new and historical geotechnical data, geological and geotechnical mapping of outcrop and rock cuts, rock strength laboratory testing and the installation of TDR, SI, and completing InSAR, LiDAR, and bathymetric surveys. This data was used to create and calibrate a 3D geology and structural geology model, including the major geologic units, major structures such as faults and their location and size.

Figure 1b shows the processed InSAR data results. The InSAR data was used for early detection and monitoring of both instability areas. Through comparison of multiple radar images captured during mine closure, and InSAR data captured prior to mine closure, deformation rates across the North and South instabilities were identified. The survey identified ongoing movements along the BI Fault in the North Instability and ravelling of material along the East Wall. However, no significant movements were detected above the crest of the East Wall, suggesting a lack of evidence for a deeper failure mechanism. Generally, the InSAR data agreed with the broader movements observed in the inclinometers and the change detection model.

LiDAR point cloud data was combined with bathymetry surveys and overlaid onto a 3D mesh model to visualize slope deformation and approximate loss of slope material. The change detection analysis showed a positive correlation with movement of the weak rock material observed during drilling. Figure 2 shows the change detection model with the red areas outlining material accumulation and the blue indicate material loss.

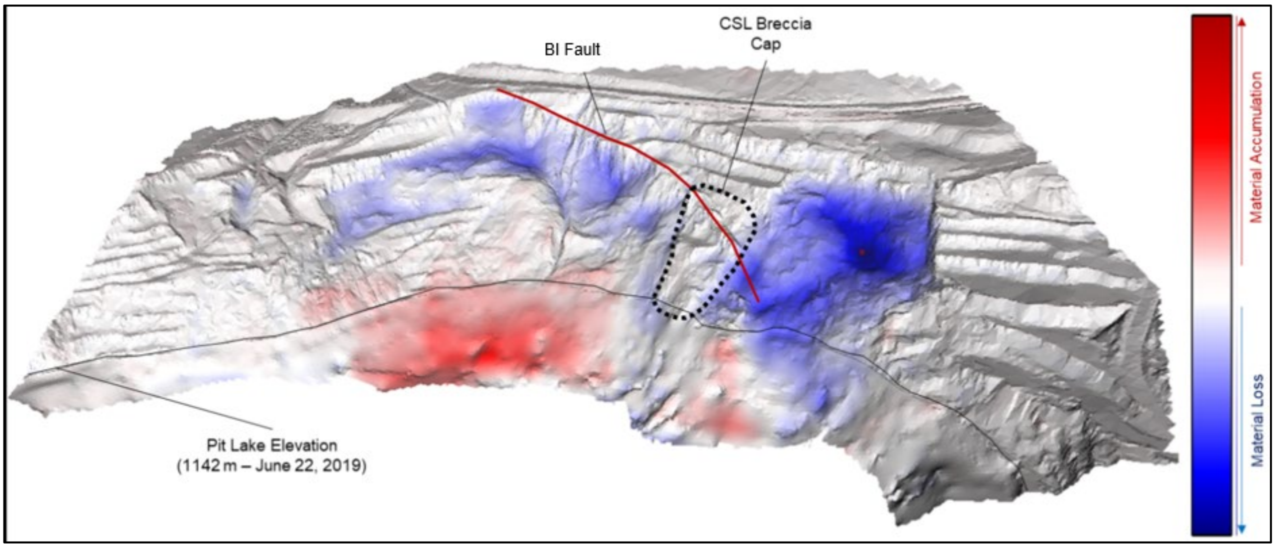

Figure 1 **Change detection between pit as-built survey and merged drone/bathymetry surveys (Saunders & LeRiche, 2021)**

The LiDAR data provided highly accurate and detailed 3D data, enabling the identification of subtle changes in elevation/surface deformation. LiDAR surveys may not be available for all projects as they are dependent on budget constraints and can be particularly expensive when covering large areas. TDR, SI, and survey methods were compared and cross-matched with each other, as well as with geological interpretations and stability analysis results. Two SI units were installed behind the East Wall. Following the installation, monitoring was carried out on a periodic frequency by the mine operator. Data collected from the SI unit information, such as movement depth, was compared to the predicted values from numerical models and calibrated to best predict slope failure setback distances.

3.2 Case study 2

This case study encompasses various phases of data collection aimed at refining the project design criteria for several project disciplines, including human health and ecological risk, tailings and waste management, mine water management and treatment, hydrogeology, rock mechanics, and demolition. The focus was on the data collection methods performed for rock mechanics assessments with specific focus on open pit stability, underground workings (the crown pillars) and underground mine openings to surface. The primary objective of open pit stability analysis was to gain a deeper understanding of the rock mass within the pit, particularly in areas adjacent to community access point, and to identify the potential risks. These analyses were employed to ensure the mine closure design is complied with provincial regulations. The geotechnical data was mainly collected during a detailed geotechnical drilling program. Orientations of the structural features (discontinuities and faults) within the pit wall rock mass were collected from oriented core logging and optical televiewer surveys. A digital elevation model (DEM) built using drone photogrammetry was used to digitally map the open pit walls. Using these datasets, joint sets and structurally controlled failure mechanisms were characterized for the long-term kinematic analysis of the slope stability as shown in Figure 3.

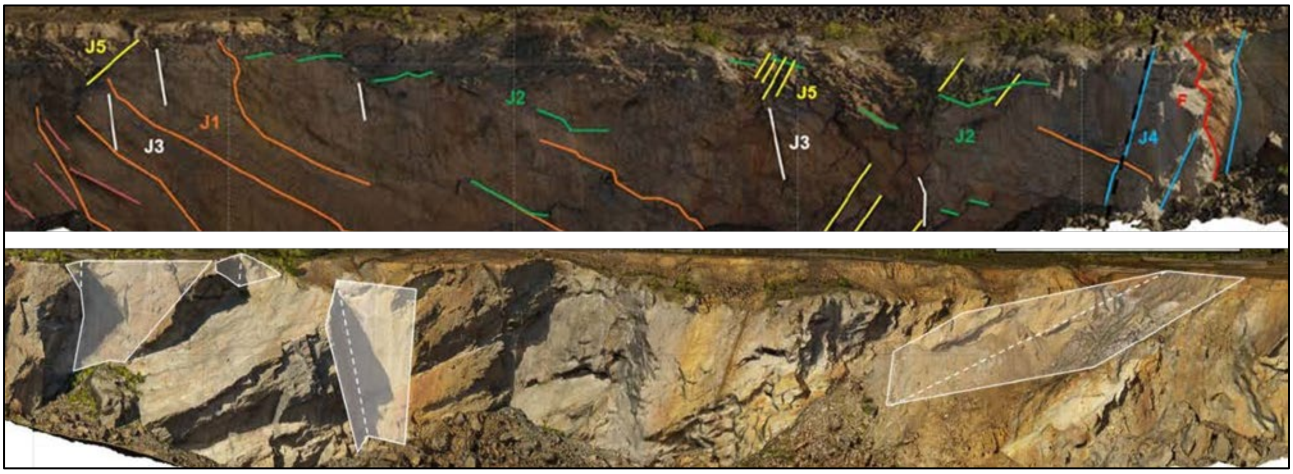

Figure 2 **Examples of structural features and structurally controlled failure mechanisms on open pit benches identified using photogrammetry DEM**

Additionally, TDR instruments were installed in eight drillholes and the TDR cables were grouted in the holes to monitor potential ground displacements along the length of each cable before they appear on surface. The system consists of a coaxial cable that is connected to the datalogger that detects ruptures or damages along the coaxial cable. These ruptures or damage are caused by movement of one portion of the rock mass relative to another. Monitoring of these changes can determine the depth and progression of the ground movement.

The focus of the mine closure planning for the underground workings were on the stability of the crown pillar. During the review of the old mine drawings and geotechnical assessments, it was discovered that a crown pillar within the mine did not meet the design requirements for mine closure, indicating a potential instability. However, the status of the stopes, whether they had been backfilled or left empty, remained uncertain. The presence of empty stopes posed a significant risk as it could lead to the collapse of the crown pillar and subsequent subsidence on the surface. To address these concerns, a geotechnical assessment was conducted, which involved a drilling investigation program. This assessment aimed to gather crucial data and insights regarding the stability of the crown pillar and the surrounding rock mass. A borehole camera inspection was completed to determine the presence/absence of backfill material, identify any major deviation along the boreholes and confirm the depth to the stope void. The borehole camera inspections at specified drillholes revealed presence of backfill (Figure 4) just below the lip of the void intersection. The survey at one of the holes encountered suspected fluid at downhole. The borehole camera lens was submerged into the fluid then retrieved back to surface to confirm that it was water.

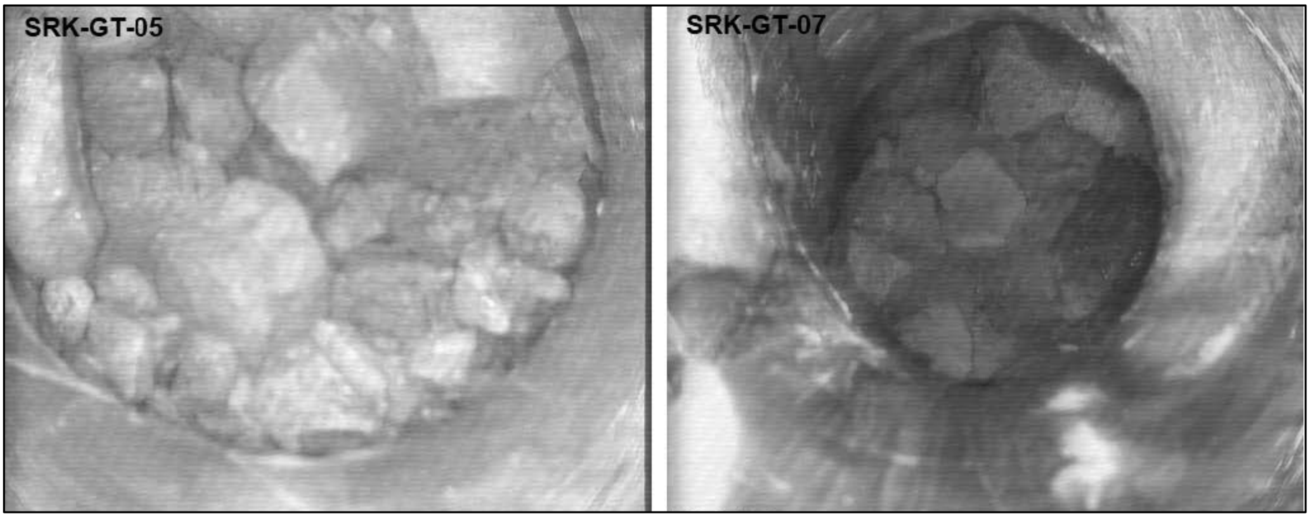

Figure 3 SRK-GT-05 and SRK-GT-07 borehole camera images

A Cavity Auto-scanning Laser System (C-ALS) was used to perform a cavity laser scan of the crown pillar above an unfilled underground excavation. The drillholes provided access to the inaccessible void, and the borehole-deployable tool determined the void's location, size, and shape. A built-in camera ensured clear drillholes and confirmed the breakthrough point. PVC pipes were inserted into the drillholes for safety and protection during the surveys. A thorough 3D analysis of the scan was conducted to identify any data gaps. Based on the scan results, one additional drillhole was added to the design to fill data gaps within the smaller stope, while another drillhole was incorporated to address data gaps along the northern extents and footwall of the larger stope. Figure 5 shows the underground stope interpretation based on the findings from the drill program, cavity laser scan survey results, and re-georeferenced old mine drawings. The multicoloured area represents the point cloud results from the laser scan. The plane representing the backfill level in the stopes, as well as the extension of the stope void are shown in this image.

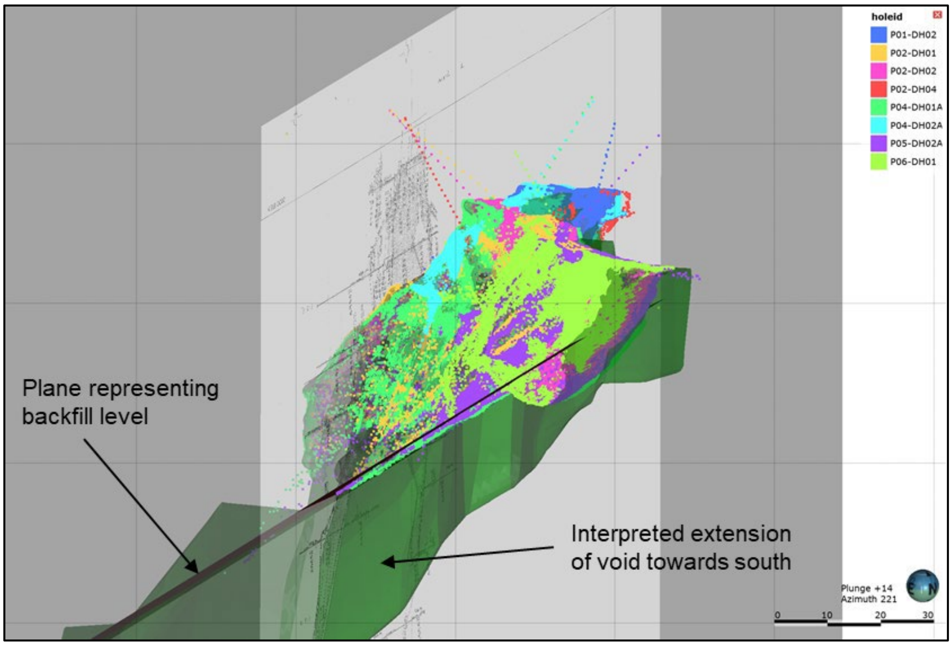

Figure 4 Cavity laser scan of the underground stope void

The objective of the shaft inspections was to determine if the shafts are viable options for the installation of water pumps and piping for water treatment purposes. The shaft inspections were separated into two phases. Phase 1 consisted of a preliminary inspection to determine if obstructions or other obstacles were present within the shaft using a borehole camera. The outcome of this work justified the detailed Phase 2 inspections, which was involved using precision LiDAR equipment to scan the shafts. In phase 1, a borehole camera was used to inspect shafts. Notable locations were identified during a downward scan, and a 360-degree sideways scan was performed at those locations during the upward imaging. Figure 6 shows key observations from the borehole camera data.

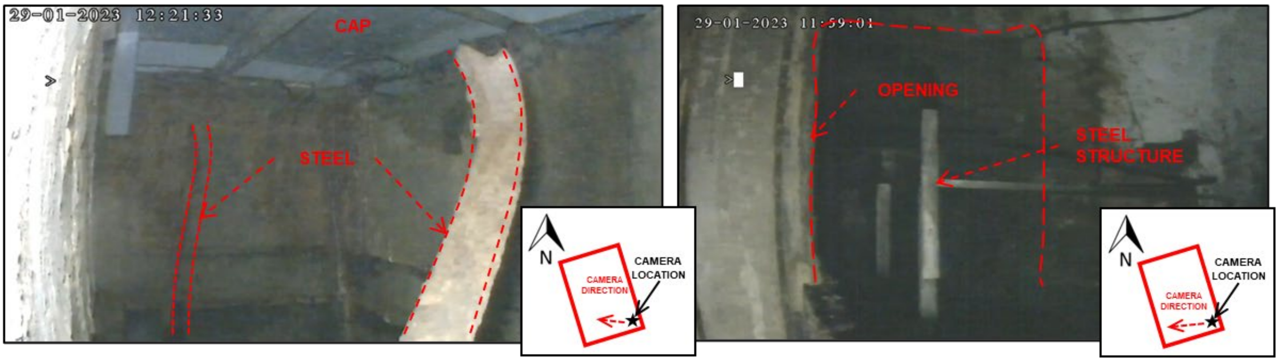

Figure 5 View of shaft from borehole camera (left) below the steel cap, (right) looking into an underground opening

Phase 2 aimed to capture rock face profiles, structures, and inspect shafts beyond the borehole camera's limit. A 3D point cloud dataset and video footage of the shaft were obtained using a LiDAR scanning system. The system employed a Simultaneous Localization and Mapping (SLAM) algorithm, capturing data at a rate of 300,000 points per second as it descended at 1 m/s. The data collection covered the entire shaft, including excavation offsets and down to a depth of approximately 220 m. Standard processing workflows were applied to reduce noise, eliminate errors, and create a continuous 3D model of the scanned section. Vertical areas of the shaft were removed, focusing on sub-vertical and near-horizontal regions. An example output is shown in Figure 7.

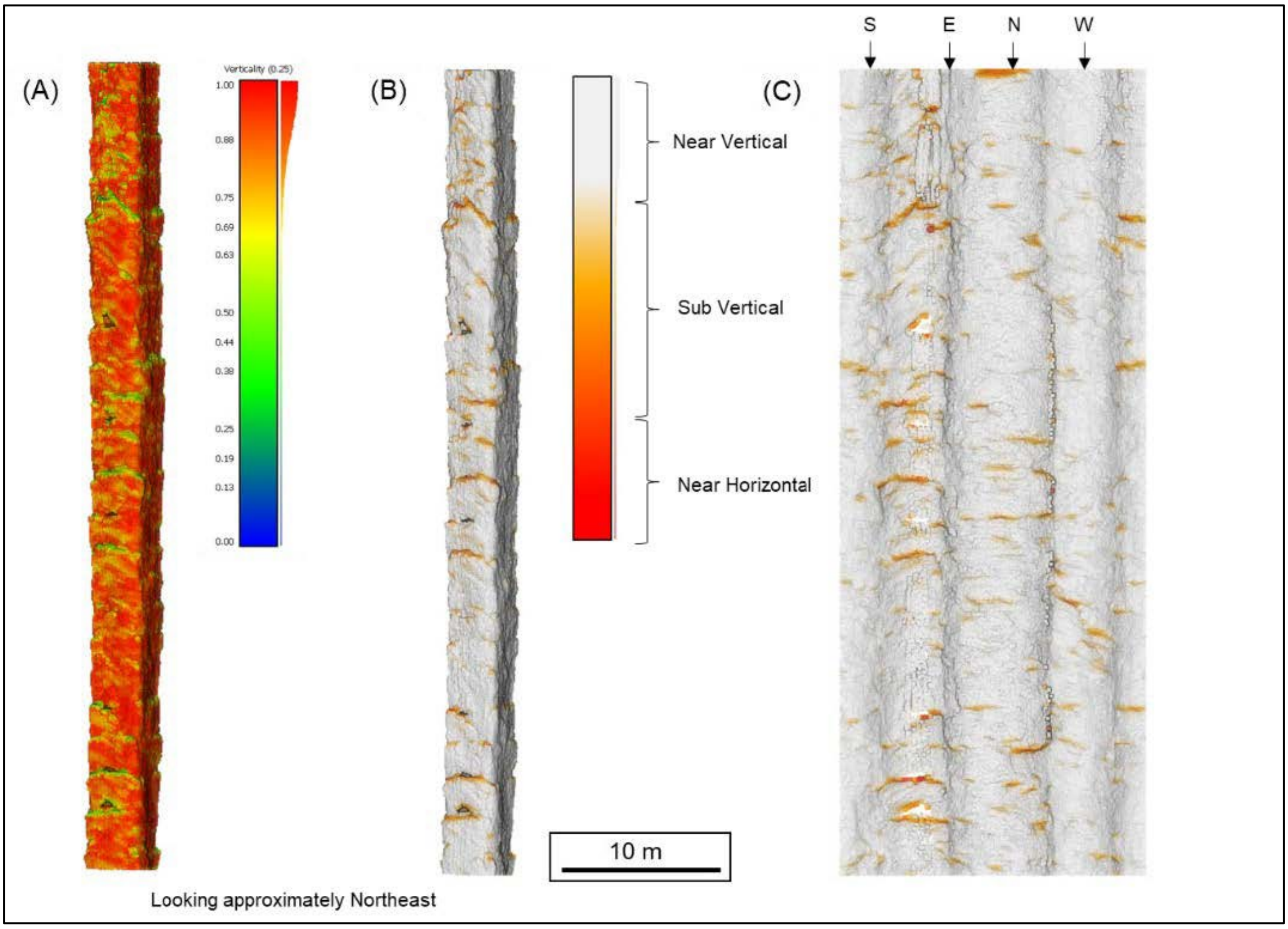

Figure 6 **Verticality computation example of the inspected shaft. (a) Displaying the full range of verticality (b) Classified values to highlight non-near-vertical surfaces (c) Unwrapped model to view the shaft interior**

Furthermore, to define a window that is clear of obstruction down the shaft, the point cloud was projected onto a zero-elevation plane and the area without points was mapped as the clearance zone. Figure 8 highlights the potential unobstructed window, approximately 1.5 m by 2.0 m, if the near-surface obstructions were to be cleared. In general, it can be noted that laser and LiDAR scanning offers a valuable solution to minimize errors by capturing millions of data points from the actual surface composition. These data points are then translated into precise models for planning and calculations. The time saved by identifying and rectifying potential errors prior to infrastructure installation outweighs the costs associated with conducting a laser or LiDAR scans.

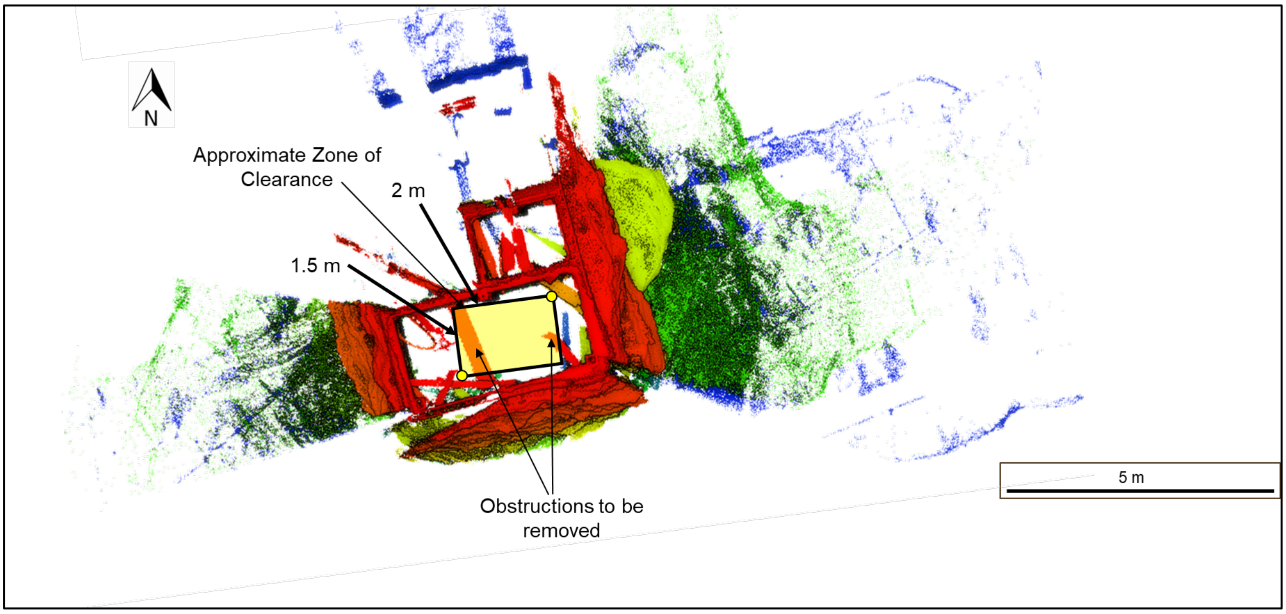

Figure 7 Potential clearance zones for one of the shafts and obstructions to be removed

3.3 Case study 3

This case study is from a mine closure project located in Northern Canada, where the objective was to obtain a thorough spatial understanding of a historic open pit and interconnected underground mine that were open and flooded. Various surveying methods were employed including a bathymetric survey and a three-dimensional sonar survey. These surveys greatly enhanced the understanding of the mine working geometries, the quality of the rock mass, potential geologic structures exposed, excavation conditions, and excavation stability. The high-quality data obtained from these surveys enabled the identification of joint sets and potential failure planes in the rock, contributing to a more thorough assessment. Given that the site had utilized interconnecting open pit and underground mining methods during its operation and had been closed for fifty years, implementing a mine closure program proved to be challenging due to the limited level of available information. Innovative approaches were therefore required to address the closure program requirements. In areas where empirical methods indicated instability, remote data collection methods were implemented to assesses stability. This included operating a survey vessel on the flooded open pit and a remotely operated vehicle (ROV) used for the underwater survey, as shown in Figure 9.

Figure 8 **Survey vessel on the pond and the remotely operated vehicle (ROV) used for the underwater survey (Hartzenberg, et al., 2021)**

A pond currently exists where the open pit was located. The bathymetry survey was conducted from the survey vessel equipped with a multi-beam echo sounder system. The survey aimed to gather XYZ coordinate files and bathymetric plans to outline the structure and notable features of a pond and underlying mining excavations. Access to the underground mine was facilitated through the open pit pond. To collect data for the survey, a survey-grade multi-beam, scanning sonar was utilized and mounted on a frame attached to the ROV. This allowed for data collection through a 3D sonar survey in areas that were inaccessible by the boat-mounted survey system. The mechanical scanning multi-beam sonar system provided high-resolution, 3D point cloud data of the underwater environment. This data was viewable in real-time on a computer at the surface and could be stored for further post-processing and analysis. Figure 10a shows the bathymetry results and Figure 10b shows the combined data from the bathymetry and 3D sonar survey.

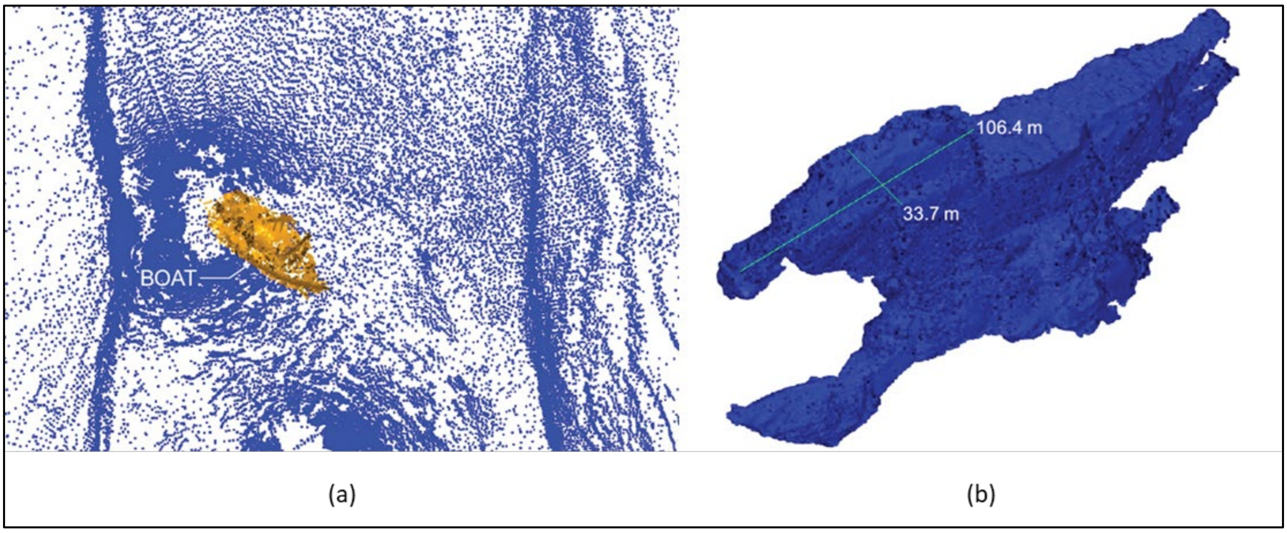

Figure 9 **Survey results. (a) High resolution scan detected a boat; (b) 3D image of the open pit pond and underground mine workings created from the combined survey data (Hartzenberg, et al., 2021)**

The mesh of the combined data provided the means to identify the pillars and backfill associated with the underground workings. Probable evidence of backfill mobilization was also determined.

Specifically, the surveys enabled the determination of the current level of backfill, condition and geometry of the hanging wall, foot wall, and crown pillar at the location shown in Figure 11. The processed survey results allowed for a visual representation of these features and the boundaries of the excavations to be created, as depicted below.

Additionally, the sonar survey data produced a high-density and high-quality mesh, enabling the identification of geologic structures. The structures identified with the mesh coincided with the discontinuity data obtained from a drilling investigation, resulting in an improved understanding of the site's geology.

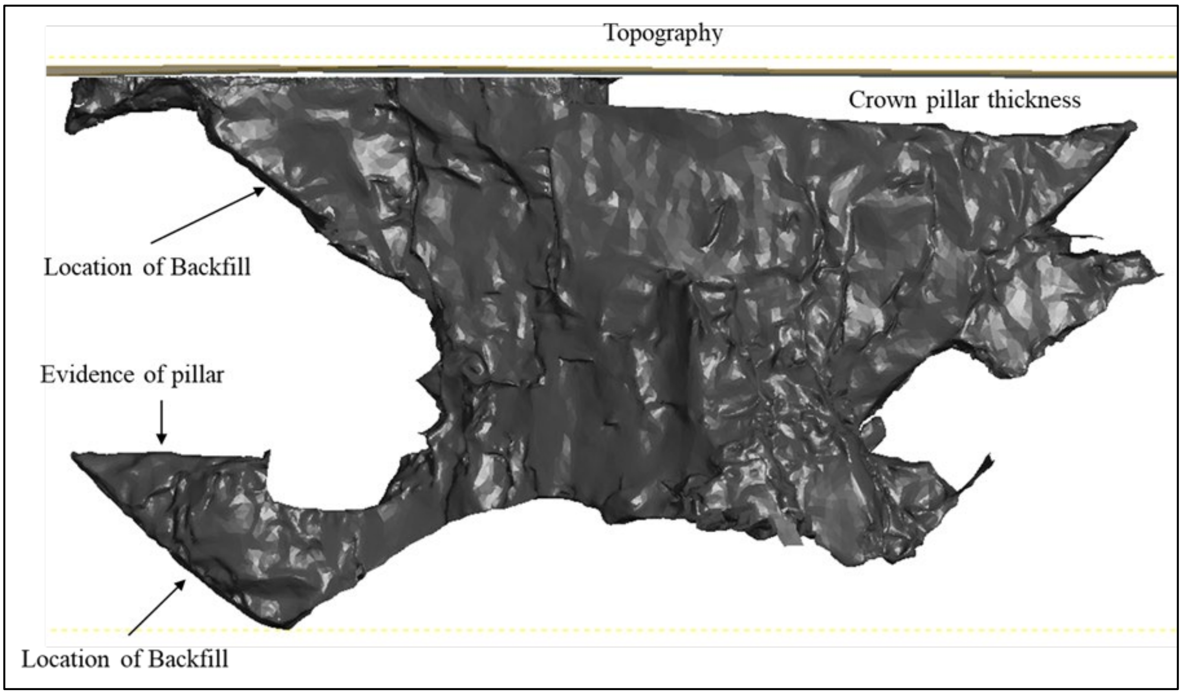

Figure 10 **Mesh of flooded underground mine workings created from sonar survey (Hartzenberg, et al., 2021)**

The surveys utilized compact and easily maneuverable equipment, making them suitable for navigating both open pit water and underwater environments. The remotely operated vehicle (ROV) proved highly effective in collecting high-quality data, particularly in confined underwater spaces, improving the understanding of underground void geometry (Joaquim, et al., 2021). These surveys offered a more efficient alternative to traditional methods, such as using 2D drawings or drilling boreholes, to gain spatial understanding of the underground workings. The data collection process typically took approximately one day, providing timely results. Additionally, the surveys prioritized personnel safety by eliminating the need for human exposure to the historic underground workings and the proximity to the crown pillar.

When using the ROV, there is a risk of cable damage or entanglement in the underground void, potentially resulting in equipment loss. Data processing can be time-consuming, particularly when converting point cloud data into 3D solids or surfaces and creating fully enclosed solids may pose challenges. The acceptance of risk associated with potential equipment loss varies depending on the site and operator, unlike drones that can autonomously return safely to the operator. It is important to note that in this case study, data collection was limited to the open pit pond, and there was no collection of lateral or vertical development data, although it may be possible in other situations.

4 Conclusion

Historical or inactive mine sites often suffer from limited or poor-quality data regarding the geometries of historic workings and stability conditions. To understand the complex ground conditions and undertake an accurate geotechnical assessment of potential risks and instability, innovative methods and technologies can be used to enhance data collection and analysis. The techniques discussed in this paper include SI, TDR, photogrammetry, LiDAR, cavity laser scanning, bore hole cameras, bathymetry, 3D sonar surveys, and InSAR methods.

The increasing accessibility of technology in mine closure projects continues to make it more feasible to implement the tools mentioned in this paper in projects with limited budgets. Technological advancements have resulted in the creation of cost-effective solutions to utilize these tools for efficient and effective mine closure projects. Each tool has advantages and limitations that are important to assess before implementation. These tools are highly dependent on budget constraints and availability of contractors.

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