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Geomechanical Monitoring of an Underground Bulk Mining Operation Using a Novel Distributed Optical Fiber Strain Sensing Method

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Abstract

As mines continue to deepen and become more expansive, active monitoring of larger volumes of rock mass will become more critical to calibrate numerical simulations and to ensure the safety of underground workers. Monitoring larger volumes of rock mass requires low-cost sensors which are simple in construction and installation. In this study, a novel hybrid optical fiber cable (HOFC) designed for use in distributed optical fiber sensing (DOFS) via grouted boreholes was employed to monitor a bulk mining operation in an underground metal mine. The HOFC was successfully used to monitor approximately 2.7×10^3 m^3 of rock mass above excavations surrounding a pillar removal area in which six large pillars were removed simultaneously. A total of six measurement boreholes (maximum depth of 22 m) were used to measure strain along the optical fiber during the pillar removal operation using the HOFC, allowing for 70 individual strain measurement points, which were constructed for under one US dollar each. Monitoring of the excavation area took place over a 44-day period after pillar removal. Extensional strains were noted in the areas closest to the removed pillars, while areas of compression were noted directly above the remaining pillar in the area. The results of the case study demonstrate that a low-cost optical fiber strain sensing network can be rapidly installed in a large excavation area and can provide highly sensitive strain measurements in a manner that would be cost-prohibitive via other methods.

Keywords Distributed optical fiber sensing · BOTDR · Bulk mining · Monitoring · Safety · Geomechanics

Highlights

- A novel hybrid optical fiber cable (HOFC) is used with distributed strain sensing to quantify geomechanical deformation after a bulk mining/pillar removal operation at an active underground metal mine.
- The use of the novel fiber optic cable for distributed strain sensing in the pillar recovery area allowed for the simple collection of data over a large area from a single or few access points, in a manner which is impractical or excessively expensive using comparable sensing technologies, such as borehole extensometers.
- Strain measurements collected directly after bulk mining are presented and used to guide interpretations on rock mass behavior in response to rapid underground excavation.

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1 Introduction

Despite a concerted effort by engineers, researchers, and mine operators, fatalities in the underground mining industry due to rock failures continue to persist. In the United States between the years 2000 and 2021, "Fall of Ground" was the most common class of fatal injury (31%) with a total of 125 individual worker fatalities NIOSH [3]. In addition, global trends in mining indicate that decreasing ore grades, such as those noted for copper [18], coupled with increasing demand will result in deeper underground excavations, and an economic favorability toward bulk mining practices such as room and pillar removal, block caving, and open stoping. Trends such as these indicate that underground excavations will be excavated faster, become more expansive, and be exposed to higher stresses and thus will require engineers and mine operators to enhance their ability to ensure the safety of workers and operational efficiency.

Officials at mines with a history of geotechnical data collection are better suited to making decisions when adverse ground conditions are encountered [10]. In general, mine operators use geomechanical monitoring for two purposes: (1) to ensure the safety of mine personnel during construction and operation of the excavation and (2) to check the validity of the assumptions, conceptual models, and values of soil or rock mass properties used in design calculations [2]—the former requires some form of immediate or real-time warning system to alert workers, and the latter becomes increasingly critical for the development, calibration, and validation of mine-scale and regional-scale numerical simulations of large mine operations.

The instruments available to mine operators to accomplish geomechanical monitoring for ensuring personnel safety and conceptual validation come with a wide range of functionalities, practicalities, and intended uses. Underground structures are typically observed by monitoring a small number of carefully chosen locations for major indicators of instability, such as increasing rock mass displacements, strains, or seismic emissions over time. The available methods, or those which are currently widely in use in the underground mining industry, can be described in terms of cost, ease of installation and data interpretation, measurement accuracy and precision, and the speed in which data can be provided to decision-makers. For example, movement indicators or other simplified devices used to alert underground workers to displacements in the immediate work environment are low-cost and easy to install and can be intrinsically safe or permissible [4, 15]. However, detailed or high-precision measurements are difficult with such devices, and they are better suited as hazard alarms [29] due to their short sensor length and their inability to record or transmit data, often requiring manual or visual data collection [15]. Underground measurements frequently make use of inclinometers and borehole extensometers [5, 24, 25],however, their employment typically necessitates placing a data acquisition system close to the monitored area, which raises the risk to the personnel taking measurements. Geodesy has recently provided an alternate technique that is ideal for such applications where a high number of control points are considered. In order to assess the safety of the tunnel excavation, electronic theodolites have been used to monitor induced deformation during tunnel excavation. The data gathered can characterize 3-D changes of the tunnel walls and compare them with the expected values [12, 13]. Due to their exposure to the difficult working environment (dust and humidity) typically seen during excavation works and mining activities, geodesic instruments, however, require frequent cleaning schedule to ensure that they are performing effectively [16, 17]. In addition, many of the available monitoring instruments can be classified as point sensors, or sensors with the ability to monitor in a highly localized area, with the notable exception of 3-D scanning or photogrammetry, which is an example of a distributed sensing technique, but has limitations when attempting to characterize the depth of failure in rock mass or make real-time measurements in underground mine environments.

A clear gap that exists in the currently utilized geomechanical monitoring technologies is the ability to monitor large underground areas in real time. As mines continue to deepen and become more expansive, active monitoring of larger volumes of rock mass will become more critical to ensure the safety of underground workers. Monitoring larger volumes of rock mass requires low-cost sensors which are simple in construction and installation. A monitoring solution that provides intuitive and actionable data is required, especially when a large area is to be monitored. Sensors which can provide information on the evolution of the rock mass from multiple points, such as near the excavation surface and deeper into rock mass, are advantageous, especially when sensors which are able to monitor progressive displacements along faults and other discontinuities are employed. This last point is especially important when monitoring data must be collected for later use in the validation of assumptions, rock/discontinuity properties, support efficacy, and the calibration of numerical models.

This research article presents the use of DOFS for monitoring a large underground pillar removal operation. The authors have demonstrated a method in which mine operators could utilize DOFS for collecting rock mass deformation data in a manner that overcomes some of the limitations traditionally associated with many of the currently available monitoring technologies (limited to point sensors, high sensor cost, manual data collection). The research is presented first with an introduction to a novel fiber optic cable which was developed for DOFS when installation of the fiber optic cable in a brittle media is required (such as a grouted borehole). The specialized strain sensing cable is then used in a field-scale case study, in which a room and pillar removal operation is monitored to measure rock mass deformation and ensure safe and efficient production.

2 Background

2.1 Distributed Optical Fiber Sensing

The strengths and limitations of the available geomechanical monitoring techniques presented in the introduction illustrate the evidence for a gap in monitoring capabilities available to underground mine operators. One such technology which is capable of filling this gap and has shown promising results for monitoring in geomechanical research and industry is distributed optical fiber sensing (DOFS). Fiber optic sensing is the practice of utilizing the physical properties of an optical fiber as a modulator to perturbations in the environment around the fiber. The fiber also works as a transducer, converting parameters such as strain and temperature into a corresponding change in optical radiation Gholamzadeh and Nabovati [6]. Fiber optic sensing has been utilized for structural health monitoring in civil and industrial settings, such as in deep unconventional wellbores [23], tunnels [16, 17], and other underground spaces [7]. The optical fiber sensing system is comprised of the optical fiber, which acts as the sensing element, and the interrogator system, which consists of a signal transmitter (light source) as well as a data acquisition and analysis system. The interrogation unit can be placed away from the site on the surface or in underground offices, because of the kilometer-scale sensing length. The fiber optic cable is relatively inexpensive, is immune to electromagnetic interference and water corrosion, and is intrinsically safe. These sensors can also be configured to provide real-time monitoring, which has attracted their use for active monitoring in pipelines, dams, bridges, and tunnels for deformation or changes in temperature.

Brillouin optical time domain reflectometry (BOTDR) is a form of DOFS that has been widely adopted for long-range (km scale) temperature and strain measurements in industrial settings. Many BOTDR sensing systems are capable of detecting changes in the optical fiber length on the order of several με and can localize such changes to within 1 m along a distance of 20 km. Figure 1 is a graphical representation of the BOTDR measurement principle: A light source is used to launch a beam of light into an optical fiber, resulting in Brillouin backscattering, the frequency of which is dependent on the longitudinal strain along the optical fiber [8]. The position of a strained area along the length of the optical fiber (between d_1 and d_2 in Fig. 1) is determined by the time interval between launching a pulse of light from a single end of the optical fiber and receiving the Brillouin backscatter signal [22].

The interaction between the incident pulsed light and natural imperfections within the silica-cored optical fiber results in spontaneous Brillouin scattering at each point within the optical fiber [14], the frequency of which can be expressed via Eq. 1:

$$v_B = \frac{2nv_a}{\lambda_p} \tag{1}$$

where v_B is the Brillouin frequency; n and v_a are the refractive index and the acoustic velocity of the optical fiber, respectively; and λ_p is the wavelength of light which has been injected into the optical fiber [1]. The change in Brillouin frequency is proportional to changes in strain and temperature via Eq. 2:

$$\Delta v_B(\varepsilon/T) = C_T\Delta T + C_\varepsilon\Delta\varepsilon \tag{2}$$

where Δv_B is the Brillouin frequency shift, ΔT is the change in temperature, C_ε is the change in strain, andC_T and C_ε are coefficients which relate frequency, in MHz, to °C or με, respectively [1]. Mechanical and thermal strains along the length of the optical fiber can be differentiated through installation techniques which isolate a section of optical fiber from mechanical strain, thus allowing for measurement of the thermal component.

One critical limitation of Brillouin-based distributed strain sensing is the meter-scale spatial resolution. When the length of optical fiber is shorter than the spatial resolution (1 m in this study), a lower-than-expected apparent strain value is produced, due to the averaging of strain measurements within each spatial resolution measurement window [20, 21]. This limitation is exacerbated when attempting to install an optical fiber cable for strain sensing in brittle media, such as cement, where highly localized strains will be imparted on the optical fiber.

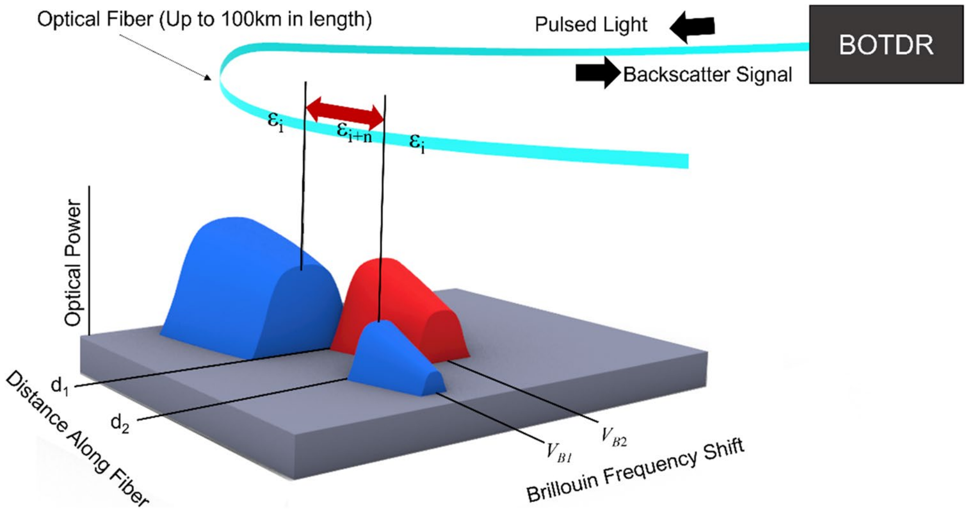

Fig. 1 BOTDR measurement principle [20, 21]

2.2 DOFS for Geomechanical Monitoring in Mining

While researchers and engineers have found many applications for DOFS in the oil and gas industry for sub-surface monitoring and characterization, applications in underground mining are limited to a small handful of case studies. A selection of case studies between 2007 and 2021 is presented in Table 1, which addresses the main observations and research gaps from each case study.

A notable item is the lack of mining-specific case studies in which DOFS is used for geomechanical monitoring. The selected papers span 14 years; however, only a small number of case studies have been reported. Several critical gaps noted in the body of literature include the inability of the developed sensors to monitor in shear strain environments, the lack of a simple-to-install optical fiber cable for sensing in brittle materials, limited interpretability of the collected strain profiles in geomechanical contexts, and the inability for researchers to relate measured strain in the optical fiber to rock mass displacements.

Table 1 Selected literature review on DOFS in field-scale mining applications

Year	Ref	Main observations	Research gaps
2007	[19]	Deformation monitoring of an underground tunnel section which was situated directly below a bulk mining zone. Point fixation method used to monitor the surface of the excavation with 3-m spatial resolution	The point fixation method in low-strain environments allows for clear displacement calculations. Monitoring the tunnel surface only allows for the detection of potential hazardous sites, but lacks granularity for the identification of kinematic failures
2018	[26]	DOFS installed in two parallel boreholes above a coal longwall face advance. Identification from strain profiles of a key layer that impacted the goaf collapse. Used resistivity measurements in conjunction with DOFS data to aid in interpretation	Use of DOFS in in-plane boreholes provides only a 2-dimensional data field. No mention of collecting displacement values from strain data. Notable difference in strain data dependent on borehole orientation
2020	[9]	Micro-anchored fiber optic cable performs well in measuring tensile cracking in lab-scale cement beams. BOTDR monitoring of a coal goaf collapse via 70-m long borehole identifies distinct zones of mobilization	Micro-anchored optical fiber is not tested in a shear environment. Monitoring data presents only distributed strain profile, and no attempt is made to relate measured strain data to rock mass displacement
2021	[28]	Deformation monitoring of a coal goaf area was accomplished with several types of fiber optics-based sensors, among them a micro-anchored cable, and an estimation of the water-flowing fracture zone was made from the collected data. Large strains were encountered during the progressive goaf failure	The high-strain environment in which the cables are installed may lead to erroneous results, especially when installed in grout/cement
2022	[27]	DOFS used in conjunction with multi-point borehole extensometers in a single borehole to monitor the progression of a longwall coal mine goaf collapse	DOFS used to identify areas of increasing strain, which was useful for identifying key strata layers, but did little for accurate measurement of geomechanical deformation, which was accomplished via other methods

2.3 The Hybrid Fiber Optic Cable

There are currently two widely accepted methods for installing a fiber optic cable on or within a structure for strain monitoring: overall (or entire length) bonding and point fixation. Overall bonding is the process of totally securing a fiber optic cable to the structure for monitoring, while point fixation is the process of securing the fiber optic cable to the structure in points along the cable. Installing fiber optic cables via the point fixation method allows for the selection of fixation intervals, which can be designed to accommodate the spatial resolution of the interrogation system and allow for the measurement of strains over the point fixation interval. The point fixation method also aids in the prevention of cable failure due to the elimination of highly localized strains upon the fragile optical fiber. Overall, bonded cables are at a high risk of failure when installed in brittle media where highly localized strains occur at cracks in the media [11].

The installation and utilization of DOFS in brittle media where the ability to install the fiber optic cables via point fixation is limited due to accessibility issues, such as within deep boreholes, are a challenging topic that requires novel fiber optic cable designs to provide measurement accuracy in areas where highly localized strains are likely to occur (cracking, displacement along discontinuities), while simultaneously ensuring that the optical fiber will not be damaged when exposed to highly localized displacements. This issue is largely ignored in many industrial applications, as the DOFS signal is mainly limited to safety monitoring, or the identification of large hazards, not for making engineering measurements or calculations per se.

For geomechanical monitoring in underground mines, grouted boreholes may be one of the simplest and most effective methods for coupling a sensor of any kind to movements in the rock mass. The ability to utilize DOFS within grouted boreholes to collect high-precision, real-time, intrinsically safe distributed measurements would provide mine operators with a much more versatile tool for monitoring than is currently available. This gap in DOFS technology has been addressed through the development of a hybrid optical fiber cable (HOFC) for distributed strain sensing in brittle media. The HOFC is an optical fiber cable designed specifically for deployment in boreholes prior to grouting operations. The HOFC is essentially a self-anchoring point fixation cable that combines the measurement accuracy and ease of interpretation of the point fixation method, with the convenient installation process in limited access spaces associated with the overall bonding method. The HOFC consists of a pair of tight buffered optical fibers which are bonded to a plenum jacket layer in intervals along the length of the cable. The intervals between bonded sections are the gauge length of the distributed strain sensor. In all other sections of the cable, the optical fiber is not in contact with the jacket layer, which prevents highly localized strains (such as those which form along cracks in grout or other brittle installation media). Micro-anchors are attached to the bonded sections with open internal spaces, which are infiltrated by the liquid grout before curing (Fig. 2). The result is an optical fiber strain sensing cable with a non-uniform profile which is capable of highly accurate measurements in shear and tension when installed within grouted boreholes. The HOFC has been tested extensively in laboratory-scale experiments, which demonstrate the effectiveness of this unique cable design in measuring displacements along highly localized tension and shear deformation zones when installed in grouted boreholes [20, 21].

3 Case Study: Distributed Strain Sensing Using the Hybrid Optical Fiber Cable in an Underground Pillar Removal Site

The HOFC was deployed at an active room and pillar removal site to aid in the identification of hazardous ground conditions and to quantify the effect of pillar removal on nearby mine infrastructure. The use of DOFS allowed for the practical and cost-effective installation of a high number of measurement points around the pillar removal area. The measurement results collected from the HOFC are presented in this work, along with a brief description of the regional geology and sensor installation process. The interested reader is encouraged to see [20, 21] for a more detailed description of the installation process and preliminary results from monitoring prior to pillar removal.

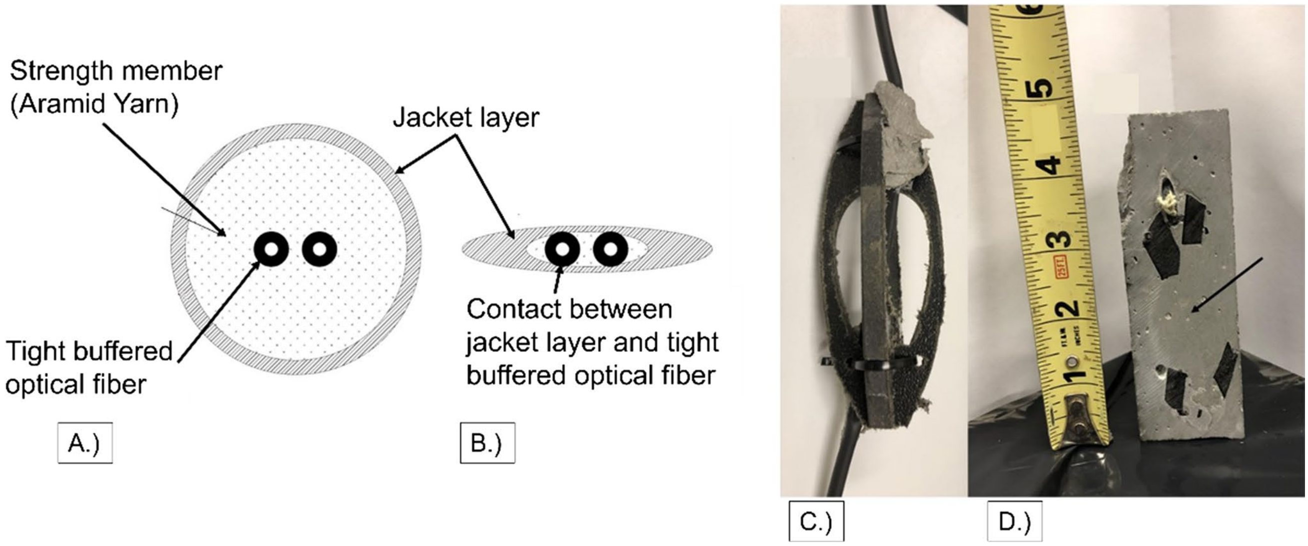

Fig. 2 The hybrid optical fiber cable (HOFC) design for strain sensing in grouted boreholes. **A** A cross-section of the unbonded section of the cable which prevents highly localized strains from occurring along the length of the optical fiber between anchoring points. **B** A cross-section of a bonded section of cable, which couples the optical fiber to the jacket layer (note that **A** and **B** are cross-sections along different parts of the same cable). The distance between bonded sections is the sensor gauge length. **C** A micro-anchor attached to a bonded section of HOFC. **D** A cemented cross-section of the micro-anchor, demonstrating how grout infiltrates the central opening of the micro-anchor (black arrow) and facilitates the coupling of the optical fiber to the grout, and thus the rock mass. Figure modified from [20, 21])

3.1 Geologic/Geomechanical Setting

The field study area is located in a breccia collapse dome structure which is hosted within a stratiform carbonate sedimentary rock package. Ore-forming minerals (sphalerite) are found filling fractures within the breccia zone, which is characterized by large angular fragments of carbonate rock (dolostones). The ore-breccia collapse dome structure is located within the Ordovician Mascot geologic formation (Fig. 3). The regional domal structure has a diameter of several kilometers. Ore-forming minerals occur throughout the dome, and a low ore-grade core of the structure exists where less mining activities are conducted. Thin shale units are used as marker beds by mine technical staff to determine their position within the stratigraphic sequence. A thin green shale unit (ID number 55 in Fig. 3) is of particular concern to the mine operator, as several ground failures have occurred in past excavations as a result of bedding separation when this unit is present in the immediate roof rock mass. Several examples of breakage or failure along bedding planes and bedding separation were noted in the study area (Fig. 4). The installed DOFS crosses the green shale maker beds, as well as other thin shale or chert beds, several times throughout the stoping area.

The complex geologic history of the site area, which involves domal collapse, brecciation, mineralization, faulting, and folding, has resulted in a wide variety of geomechanical conditions that must be navigated by the mine operator. Bedding planes are generally characterized by shallow dips (< 20°), and the condition of joint planes is good, with slightly rough surfaces and little to no infilling. The estimated rock mass rating (RMR) values in these operations range from 64 to 85.

3.2 Site Selection and Sensor Installation

A random room and pillar stoping area was selected for the DOFS monitoring program. The stoping area has an average overburden depth of 275 m, and pillars in the area range from 10 to 20 m in height. Pillars in the measurement area consist almost entirely of mineralized breccia (Fig. 5).

An installation plan was devised to provide geomechanical monitoring coverage to two main access points into the room and pillar removal stope. Access for ore removal would be conducted via automated Load Haul Dump (LHD) machines. A series of 12 boreholes were drilled throughout the stope, some (holes 4–8 and 10) were drilled at a 45° angle into the excavation rib to a depth of 27 m. The remaining holes were drilled into the excavation roof

Fig. 3 (Left) Generalized cross-section of the collapse breccia. (Right) Stratigraphic sequence of the Mascot Formation with thin shale and chert marker bed identification numbers

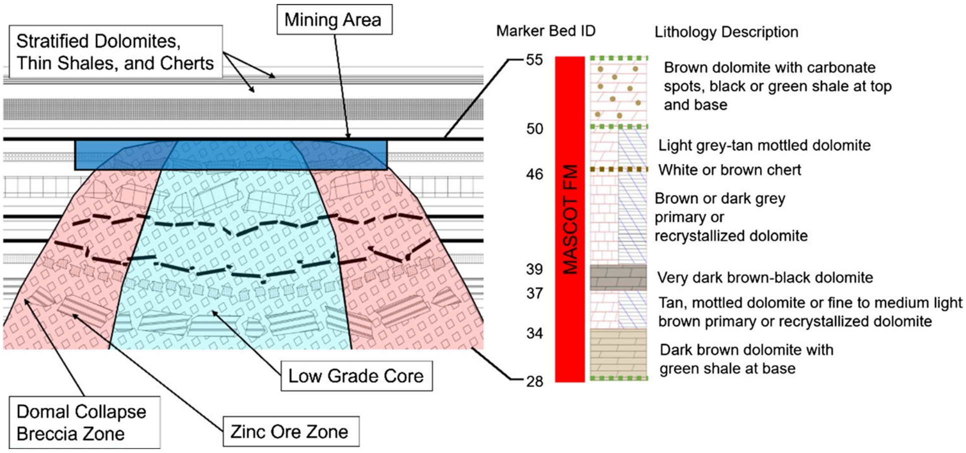

Fig. 4 (Left) Breakage to bedding planes noted in the measurement area. (Right) Small roof failure due to bedding separation in an area where the number 55 thin shale marker bed is in the immediate roof section

Fig. 5 (Left) A 10-m high pillar located in the measurement site. (Right) Brecciated dolostones with mineralized sphalerite

at an angle of 80° to a depth of 22 m or shorter. The installation plan in this case study was designed for use with a double-channel BOTDR interrogation system (location denoted in Fig. 6). As the mine operator did not require real-time monitoring for this case study, no additional cable was required to network the interrogation system to an Internet access point. This could be achieved with relatively little additional work, however, and well within the operational capabilities for the fiber length of the interrogation system. The fiber path for the installation plan is comprised of one large loop throughout the stope, which is interrogated at both ends simultaneously. This configuration has advantages in that a single cable breaking point will result in no data loss.

The HOFC was deployed and installed in all 12 measurement boreholes. Micro-anchors were installed at the interval bonded sections, which were spaced at 1.5 m increments along the length of the cable. At each borehole, the first anchoring point was secured to a polyvinyl chloride (PVC) tube, which was used to insert the sensor into the toe of the borehole. The optical fiber cable is looped at the toe of each hole, such that a single continuous loop can be maintained throughout the stoping area (Fig. 7). It should be noted that micro-anchors were only attached to the cable on one side of the loop in each borehole. The PVC tube used to insert the HOFC into the toe of the hole was used as a breather tube to evacuate the air in the borehole as the grout was injected at the collar. Expanding foam was used to seal the collar of the borehole and prevent grout from leaking. After installation of the HOFC in each borehole, grouting operations began and ceased after grout was noted ejecting from the exposed end of the breather tube, which indicated that grout had reached the toe of the borehole. The grout used to install the HOFC was allowed to cure for

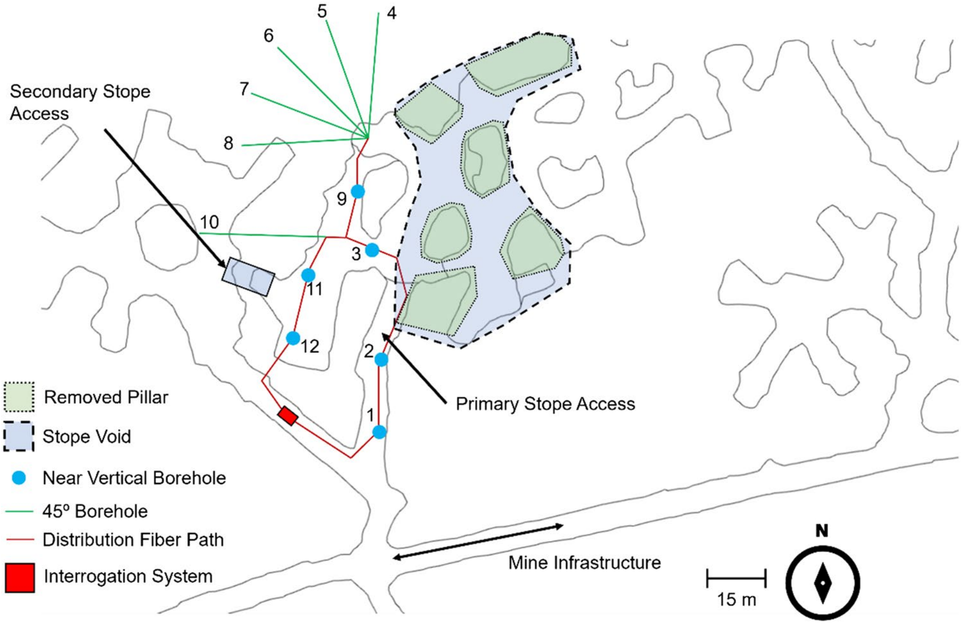

Fig. 6 Mine layout with optical fiber path and locations of removed pillars in relation to mine infrastructure

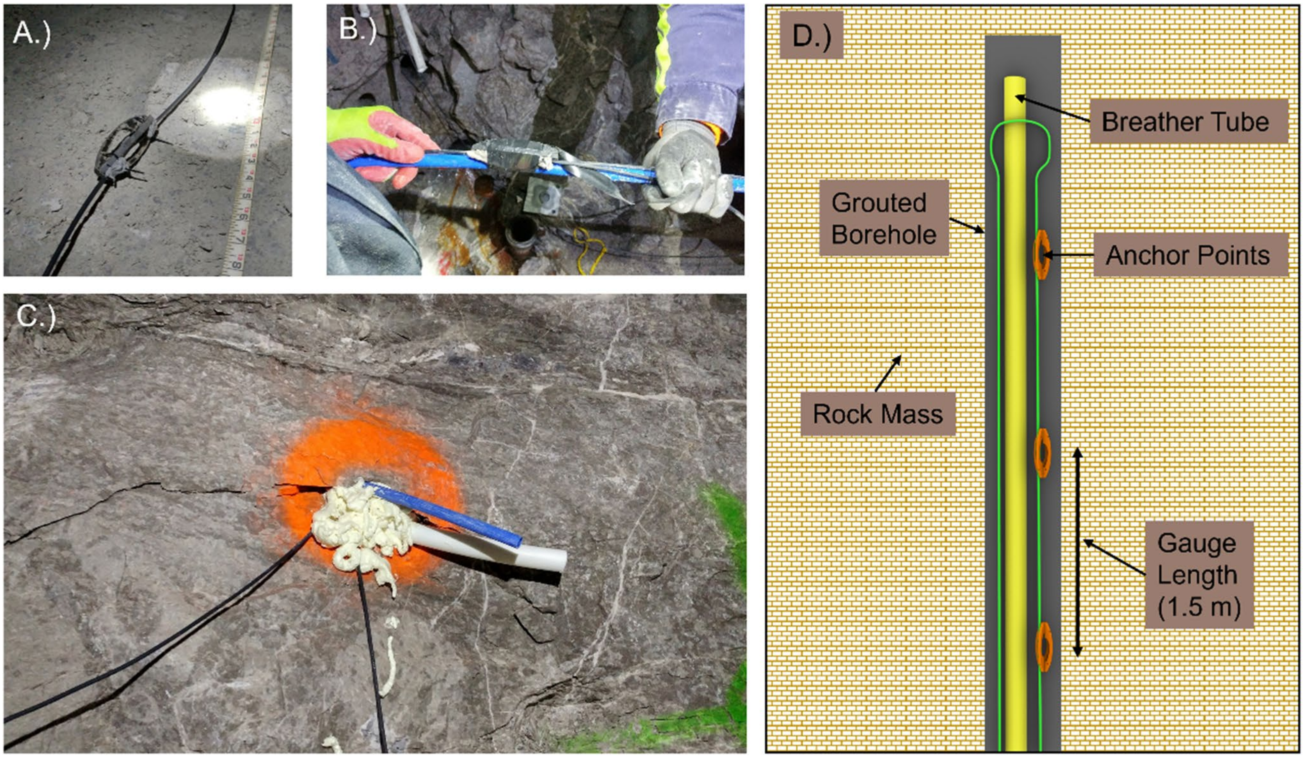

Fig. 7 **A** HOFC with installed anchor point. **B** First anchor attached to breather tube for insertion into a measurement borehole. **C** The installed sensor ready for grouting. **D** Schematic diagram of the installed HOFC

the typical 28 days, and no mining activity was commenced for a period of 6 months after cable installation to provide a baseline for temperature fluctuations. The fiber cable used between boreholes was secured to welded wire mesh on the roof of the excavation using cable ties. In this configuration, the cable between measurement boreholes was not used for strain sensing purposes. The interested reader is referred to [20, 21] for a more detailed description of the installation procedures.

3.3 Pillar Removal Monitoring

A total of six mine pillars were simultaneously removed from the measurement site on May 5, 2022, via blasting of ring-drilled boreholes. As expected, the resulting blast and fly-rock damaged portions of the optical fiber network, limiting access, initially, to holes 1, 2, 11, and 12 (see Fig. 8). Access was gained to the Western portion of the stope by the construction of a breakthrough drift. Through this additional

Fig. 8 Stope condition immediately after pillar removal. The red arrow indicates failed friction bolts noted in the stope. Red circles indicate locations where the fiber optic cable was severed between measurement boreholes

drift, the researchers were able to regain access to holes 9 and 10 to collect measurements 44 days after pillar removal.

Roof failures in the pillar removal area began to occur immediately after bulk mining procedures. Failures past the primary roof support were noted immediately after mining, and failures up to the 55-shale bed in the area (~ 12 m vertically from the roof) occurred and concluded sometime between days 10 and 44 (Fig. 8).

Figure 9 presents the collected relative strain measurements from 2, 10, and 44 days after the pillar removal from all accessible boreholes. Relative strain measurements are made against a post-cure baseline measurement, which sets all existing strains in the optical fiber (such as those from installation and heat expansion during grout curing) to zero. This allows for any strains introduced from mining activity to be recorded as relative strains to the baseline measurement. A positive relative strain value corresponds to a lengthening of the optical fiber (in tension or shear), while a negative relative strain value corresponds to a shortening of the optical fiber (in compression). Boreholes discussed in this section are drilled nearly vertically (+ 80°) into the roof or back of the excavation, with the exception of borehole 10, which is drilled at an angle of + 45° from the sidewall or rib of the excavation. Strain measurements are presented here with relevant information, such as the approximate location of geologic contacts along the fiber path. The locations of geologic contacts with respect to the excavation roof have been provided by technical services personnel at the active mine site. It should be noted that the first 2.1 m of each measurement site has been bolted with friction bolts.

4 Data Investigation

Any novel sensing method which is used beyond its traditional usage patterns requires a level of scrutiny to develop measurement confidence in the transition from laboratory-scale testing to usage in the field. As no other sensing methods were able to be applied in this study due to operational limitations, several occurrences from the collected data before and after the pillar removal operation were used by the researchers to ensure that the HOFC had been installed correctly and that measurements collected after the pillar removal could reasonably be attributed to geomechanical deformation, and not to an erroneous sensor installation.

4.1 Measurement of Curing Grout in Boreholes

During the installation of the HOFC at the active mine site, class 1 Portland cement was used for grouting the fiber optic cable in place within the boreholes. Typically, 21–28 days are required for grouted boreholes to be considered fully

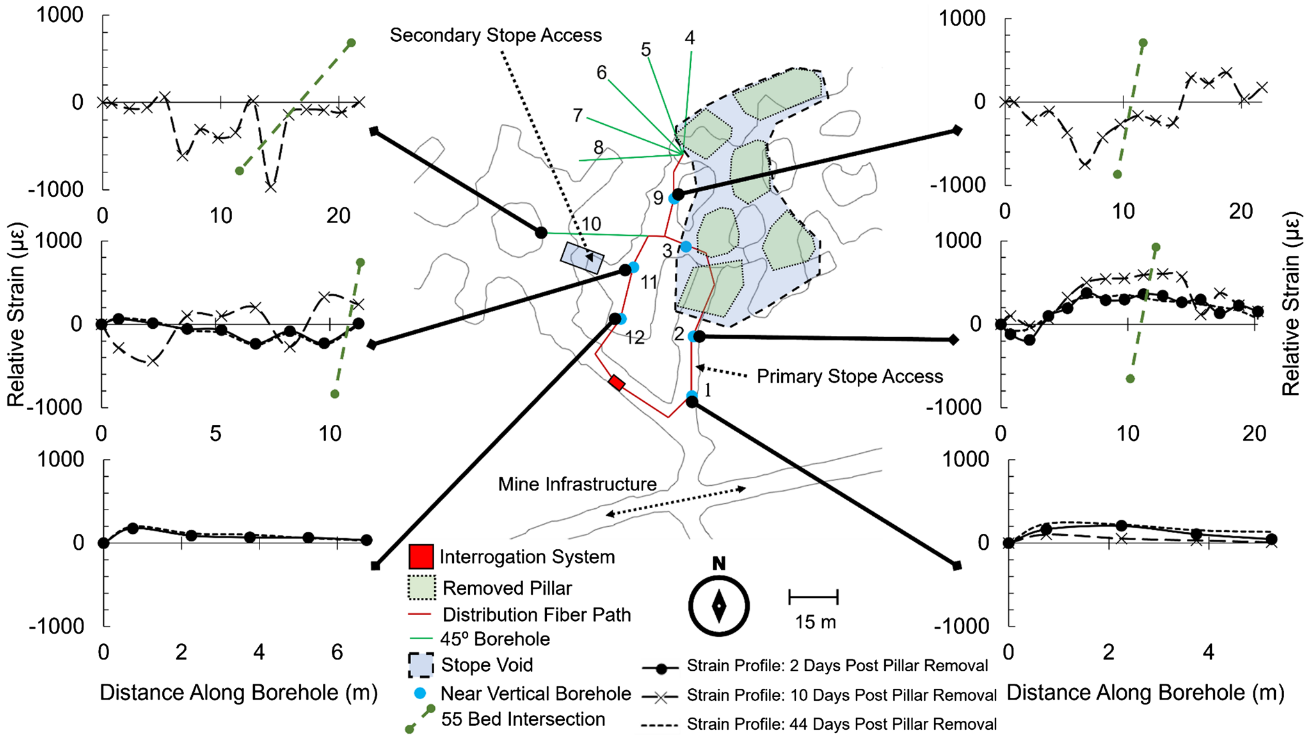

Fig. 9 Collected relative strain measurements from all accessible boreholes at 2, 10, and 44 days after pillar removal. Note: Tension of the optical fiber is denoted by a positive strain, while compression is denoted by a negative strain

cured. As the curing process results in the dissipation of thermal energy as well as shrinkage, cracking, and hardening of the cement within the borehole, it is difficult to obtain meaningful geomechanical data from the DOFS during this period; however, strain measurements have been made within the boreholes, which indicate that the installed sensing system is functioning properly. An increasing measured strain value was captured from the DOFS installed within borehole 5 (see Fig. 6 for borehole location). Successive relative strain measurements were selected and overlain to identify regions of progressive strain changes. Figure 10 is a compilation of select relative strain measurements from a 17-day span, starting several hours after grout installation within the borehole.

A pair of strain peaks developed over the course of the grout curing period (black arrow in Fig. 10). The two peaks spaced ~ 1.5 m apart along the trace of the fiber path likely correspond to the mid-point between two anchoring points on the HOFC, with the trough between the peaks indicating an anchoring point that restricts the strain in the cable in that area. Recall that anchoring points along the HOFC are spaced with a 1.5-m interval. This elevated strain measurement likely corresponds to shrinkage cracking in the curing grout; however, it is interesting to note that the location of the strained cable corresponds almost exactly with the intersection of borehole 5 with a thin, green shale lithology change. It should be noted that borehole 5 was the only location in which this type of straining was observed.

Local air temperatures in the stoping area excavations were near constant, and little fluctuation was noted during the course of the monitoring study; thus, temperature correction was foregone for this study. It is assumed that temperatures will fluctuate considerably less within the rock mass than in the ventilated mine openings, which is evidenced by the near-constant strain profiles collected along unstrained portions of the DOFS during 6 months of mining quiescence before pillar removal, as well as those collected along portions of the DOFS in contact with the circulating mine air.

4.2 Strain Mirroring

The HOFC is installed in a looped configuration; thus, two sections of fiber optic cable are installed along the length of each borehole, with a loop at the borehole toe. It should be noted that bends in the optical fiber do result in a loss of optical power, but for short installations (1–5 km) or for relatively few boreholes, this does not present an operational issue. Due to the installation configuration, strain measurements along the anchored section of the HOFC in the grouted borehole may be "mirrored" along the other side of the cable installed within the same borehole. As this section is bonded (as described in Fig. 2B) but not anchored, we may not expect a perfectly accurate strain measurement, but a similar measurement would indicate that both lengths of cable are passing through the same strain field. If desired, this behavior could be avoided on the return side of the cable by isolating the cable from mechanical strain via insertion into a flexible tube. This behavior was noted in several of the boreholes (2, 9, and 10), but most prominently in borehole 2 after the pillar removal, where the highest positive strain values were noted. Strain mirroring in borehole 2 (Fig. 11) can be seen by comparing the anchored side of the installed cable within the borehole (from 76 m along the fiber to 99) with the unanchored side of the cable which is looped at the toe of the hole and is hung alongside the anchored side of the cable (from 99 to 122 m). The two notable strain peaks (between points A and B and points B and C) are located in

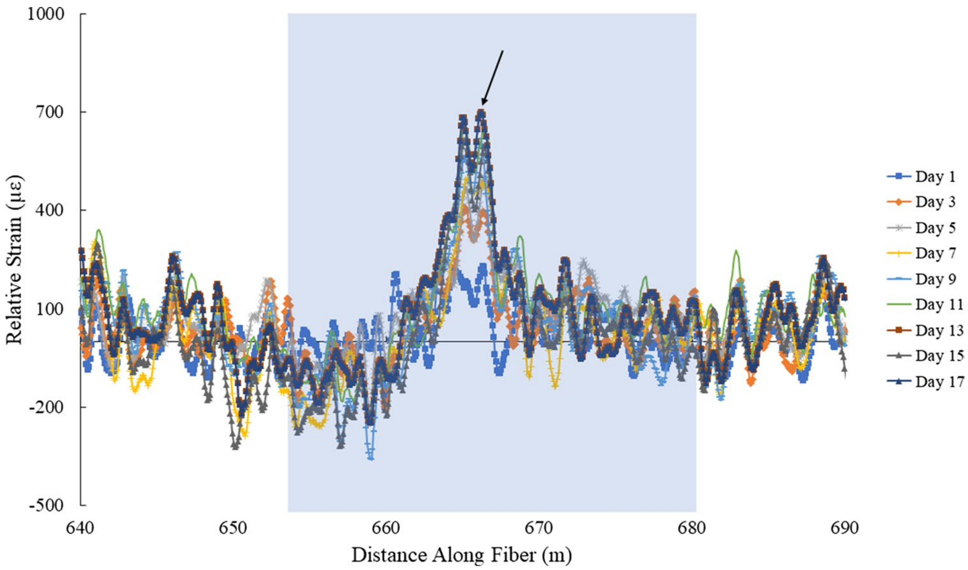

Fig. 10 Relative strain measurements from borehole 5 (HOFC installed within a borehole is highlighted in blue). Strain profile labels indicate the number of days after grout placement. The arrow points to the location of a double strain peak separated by 1.5 m of cable (modified from [20, 21])

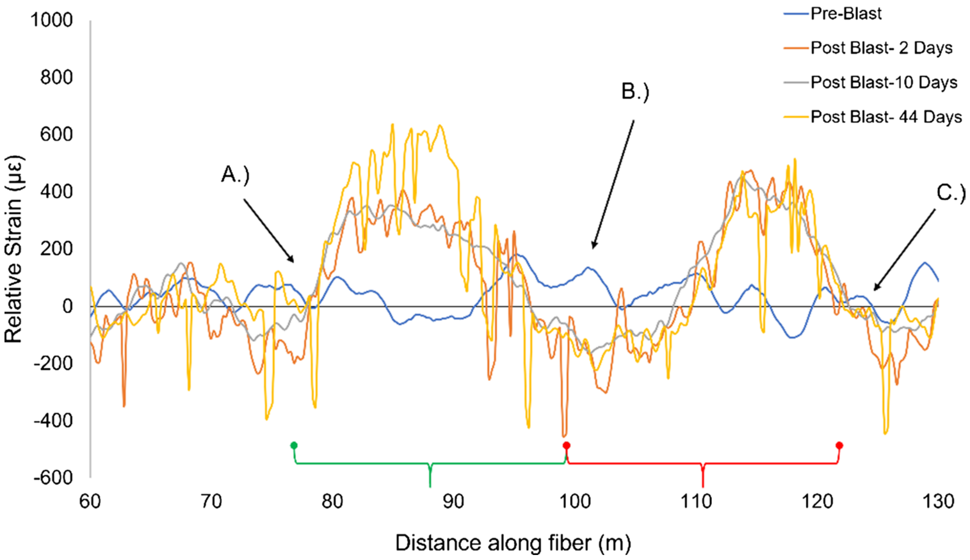

Fig. 11 Evidence of strain mirroring captured in borehole 2 after pillar removal. (A), (C) The location of the borehole collar along the fiber trace. (B) The location of the borehole toe along the fiber trace. The green bracket indicates the section of the HOFC which was bonded and anchored, while the red bracket indicates the section of the HOFC which was bonded, but not anchored

generally the same location within the borehole and, thus, are both within the same strain field.

5 Data Interpretation

The DOFS network installed around the pillar removal area has generated a large amount of data that can be interpreted to provide insights into the geomechanical deformation which results from bulk mining practices. Strain signals, both positive and negative, are generally of a lower magnitude with increasing distance from the pillar removal area. Positive strains indicate a lengthening of the cable and can be relied upon as accurate measures of strain from laboratory testing [20, 21]. Negative strains indicate a shortening of the cable and are far less reliable beyond identifying areas of compressional strain in the rock mass. Borehole 2 is situated within 5 m of the stope opening and is the closest of all the boreholes in proximity to the stope. Positive strains were measured in almost the entire borehole length, indicating that an extensional deformation had taken place in this location after pillar removal. In addition, the largest strained area was noted to occur above the intersection of the borehole with the 55-thin shale bed, which indicates potential de-lamination of the bed with the underlying strata, and an extension of the material above the de-laminated area.

While compression of the optical fiber cannot be reliably used to assess strain magnitudes, negative strain signals can be used to identify compressional zones within the rock mass. These areas occur most notably in boreholes 9 and 10, which correspond to the remaining pillars in the stoping area. After pillar removal, excess vertical loads would be expected to be re-distributed to the remaining pillars, which correspond well to the measured signals. The positive strain

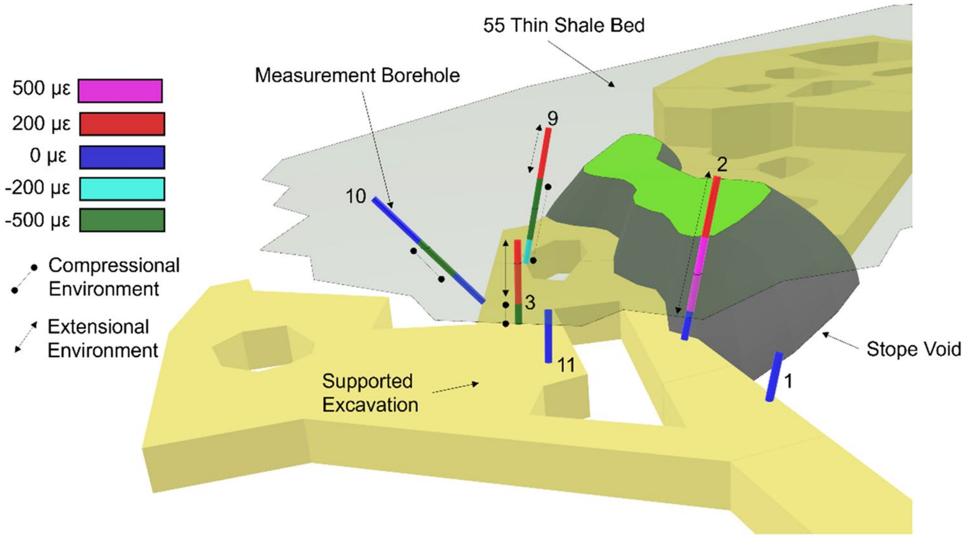

Fig. 12 3-D excavation map with measurement boreholes and relevant geologic contacts

values collected near the toe of borehole 9 indicate that bedding separation may have occurred around the 55 thin shale bed, resulting in compressional loading on the remaining island pillar, which borehole 9 is drilled above (Fig. 9). In many of the measured strain signals, the area of installed sensor which corresponds to the supported zone (from 0 to ~ 2 m along the borehole traces) of the excavation experienced comparably little strain to areas further into the rock mass which were not supported, suggesting that the installed friction bolts aided to limit rock deformation in the areas in which they were installed.

Areas with similar strain values within the boreholes can be averaged and contoured. Strain contours can then be superimposed on the 3-D excavation map, along with relevant geologic information (Fig. 12). This visualization allows for the identification of extensional and compressional deformation zones and demonstrates that contours of similar strain signals could be drawn around the study area for use in validating engineering assumptions regarding rock mass properties, excavation geometries, and support designs.

6 Conclusions

A novel hybrid optical fiber cable (HOFC) is used with distributed strain sensing to quantify geomechanical deformation after a bulk mining/pillar removal operation at an active underground metal mine. The use of DOFS allowed for simple and rapid sensor installation over a wide area. The cost of the installed sensor was significantly lower than what would have been achievable using comparable instrumentation, such as borehole extensometers with a similar sensor density. The HOFC overcomes several limitations facing DOFS installation in brittle media where direct access to the sensor is not possible, such as within grouted boreholes. The HOFC allowed for the measurement of rock mass deformation after pillar removal mining in a high-stiffness rock mass environment where little deformation was expected. High extensional strains detected in an access point to the pillar removal stope allowed the mine operator to select a different access point, thus ensuring operational continuity.

Rock mass strains in both compression and tension were detected by the monitoring system, and the highest magnitudes of strain were encountered in close proximity to the intersection of the measurement boreholes and a stratigraphic thin shale bed which was noted to result in bedding separation elsewhere in the mining area. While compressional strains detected by the HOFC are not reliable in magnitude, they occur in areas where compressional rock stresses would be expected after load re-distribution due to pillar recovery.

The use of the HOFC for DOFS in the pillar recovery area allowed for the simple collection of data over a large area from a single or few access points, in a manner which is impractical or excessively expensive using comparable sensing technologies, such as borehole extensometers. This technique allows for the detection and localization of failure depths, which would complement the distributed surficial monitoring of LiDAR scanning techniques for mine safety.

Through the collection of high-precision, high-density rock mass measurements during bulk mining operations, the research team aims to aid in the calibration or validation of mine-scale numerical models, which, when properly calibrated through monitoring data, can be useful for forward analysis of more complicated mining scenarios.

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Data Availability The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics Approval Not applicable.

Consent for Publication All authors agree to publication in the journal.

Conflict of Interest The authors declare no competing interests.

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