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Experimental evaluation of a distributed Brillouin sensing system for detection of relative movement of rock blocks in underground mining

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1. Introduction to deformation monitoring premise

Underground mining in highly stressed, hard rock masses is commonly accompanied by seismic events that are located close to mining, near active stopes and other excavations, most frequently within one diameter of the excavation boundary. However, as the extraction ratio increases or mines progress to greater depths, remote events have been observed at large distances from active mining, where the direct mining related stress changes are negligible. Events in different mining blocks cannot be explained by models involving stress redistribution processes alone.

Some authors[1] suggest that remote seismicity occurs where geological features, especially faults, intersect a mining zone. In order to generate seismic events, such faults have to be close to the critical stress state for slip under the existing regional stress field, such that even small perturbations in the local stress field could cause slip and generation of seismic slip event. Although large seismic events have often been observed and attributed to slip on pre-existing geological faults, it is hypothesized here that shear bands can form and develop over time during a mine's life. In other words, rock bridges can gradually be weakened as mined areas expand, and a discontinuity plane gradually coalescences, offering more kinematic freedom as mining develops.[2–4]

Based on records of distant events (> 100 m) that occurred at the Creighton Mine in Sudbury, Ontario, Kaiser et al.[3] raised the possibility that the interdependence of widely-separated seismically active areas could be explained by gravity-assisted, deformation-controlled process in the rock mass. They used a "train analogue" to describe the sequential movement of rock blocks from close to the mined boundary to remote distances. As soon as the train locomotive starts to move, the first wagon begin to displace but the displacement wave gradually propagates from the nearest attached car to the last car at the end of the train but with some retardations.[5] The retardation in displacement and the transfer of forces depends on the geometry of the car assembly and the characteristics of the couplings. Applying this analogy to a rock mass, understanding when and how much each individual block displaces provides important information about the displacement transfer rates and rock mass deformation pattern evolution. As shown in Fig. 1, knowing the displacement field between two or more openings experiencing seismic activity (e.g., along profile AA') is thus central to an improved understanding of the time, location, magnitude and probability of remote seismic event evolution. The train analogy presented in[3] is similar to the slider block model proposed by Burridge and Knopoff [6] to explain the temporal and spatial interrelationship between sequential earthquakes, showing how cumulative small events may eventually trigger larger events. The remote seismic events can either happen around large geological features such as fault if they are critically stressed (events around fault at Fig. 1) or they would be caused by the gravity driven deformation process of the rock mass moving toward mining stopes, as indicated by downward arrows in Fig. 1. Note that the microseismicity at A and A′ occurs because of significant stress change.

Conventionally, strain measurements in underground mining involve point sensors and displacement measurements are conducted

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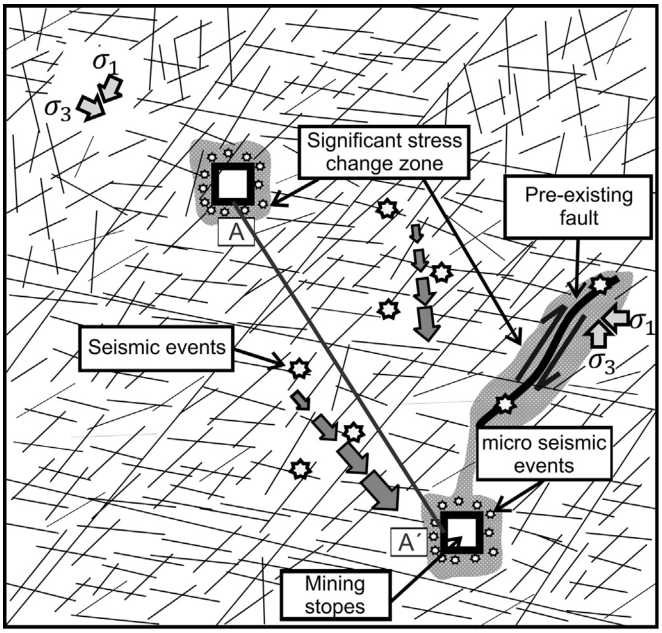

Fig. 1. Seismic events located remote from active mining areas might be associated with the rock mass movement toward openings over time with increases in extraction ratio (shaded areas highlight where the direct excavation-induced stress change might be significant). Continuous rock blocks displacement measurements between A and A′ could help understanding deformation-induced, remote seismicity.

with multipoint sensors such as extensometers allowing displacement monitoring between a limited number of anchors. These techniques are typically restricted to the near-field of excavations because of drilling and instrumentation limitations. Therefore, to study whether correlations exist between rock mass displacements and remote seismic events, would require new, far-field monitoring capability that could provide a comprehensive insight into the displacement field between openings and mining blocks (i.e., at the 10's to 100's of meters scale).

Recently developed distributed Brillouin sensing (DBS) systems are strain monitoring devices that, in conjunction with purpose-built fiber optic sensors, can provide a continuous strain field over large distances. They have been successfully applied in many engineering fields, e.g., for monitoring electrical power lines,[7] oil and gas pipelines,[8] coiled tubing,[9] concrete and steel bridges,[10–12] composite structures,[13] embankments and dams,[14,15] landslide activity and slope stability assessment.[16] They have also been used to monitor underground excavations including shallow tunnels [17] and underground mines[18–20] but not for the purpose described above.

In the present study, a DBS has been adopted for laboratory-scale testing to evaluate its capability and limitations for monitoring deformation patterns in long boreholes for mining application. The main objectives of this research include the DBS response to various deformation sequences and spatial configuration, the ability to detect joint opening with the sensing cable embedded in the borehole filler, the optimum installation method, and the effect of mechanical properties of the filler on the strain transfer process from host rock to the monitoring cable.

2. Working principles of DBS

The light sent into an optical fiber is scattered in all directions, with maximum losses in the backward direction. There are three types of light scattering in an optical fiber: Rayleigh, Brillouin, and Raman scattering. Among these kinds of light scattering, Raman and Brillouin scattering have found applications in measurements of distributed sensors. The scattered Raman light has a frequency shift in the range of ± 10–13 THz with respect to the incident light, whereas this is in the range of 10–13 GHz for the Brillouin scattering. The intensity of the Raman scattering light shows high sensitivity to temperature change (ΔT), making it a reliable and widely used temperature sensing system.[21]

In Brillouin scattering, the scattered light reaches a peak over its spectrum at a frequency shifted from the pulsed light, known as the Brillouin frequency shift, ν_B:

$$\nu_B = 2nV_a/\lambda_o \tag{1}$$

where, n is the effective refractive index of the fiber, V_a is the acoustic wave velocity in the fiber core, and λ_o is the vacuum wavelength of the incident light. Acoustic wave velocity is dependent on changes in temperature and density due to strain along the sensing fiber, as is the Brillouin frequency shift, given by

$$\nu_B = \nu_{Bo} + C_\varepsilon \Delta\varepsilon + C_T \Delta T \tag{2}$$

where ν_{BO} is the Brillouin frequency at the initial reading at a given (T, ε) condition, and $\Delta\varepsilon$ and ΔT are the stain and temperature variation at subsequent measurements, respectively. Brillouin scattering sensing is best for strain measurements and in principle can provide a spatial resolution around 1 m in a 50 km long fiber.[9,22] The resolution of the measurement can reach 1 °C for ΔT and 2×10^{-5} for $\Delta\varepsilon$.

Among available Brillouin scattering sensing technologies, two types are most commonly applied. The first works based on spontaneous scattering called Brillouin Time Domain Reflectometry (BOTDR) with a need to access only one end of the sensing cable. The other is a stimulated scattering system, called Brillouin Time Domain Analysis (BOTDA), which requires access to both ends of the sensing fiber.[23]

In a stimulated scattering method, BOTDA, a weak continuous light source called the probe beam is back propagated into one end of the fiber while a high amplitude pumped pulse is simultaneously sent into the other end. The stimulation process, i.e. gain, becomes maximized when the frequency difference between these two beams is equal to the Brillouin frequency shift. The gain process is accomplished through monitoring of the power transfer ratio from pump to probe beams at certain light frequencies in a step-wise manner. Thus the Brillouin gain spectrum can be locally reconstructed and interpreted when the gain as a function of frequency at any individual sampling point along the fiber optic cable is analysed.

The DBS system used for the present study is a BOTDA commercially known as DiTeSt™, manufactured by Omnisens SA. Table 1 gives the DiTeSt™ configuration used for measurements in the study. Furthermore, a special fiber optic cable, called SMARTprofile™ made by Smartec, was used as the sensing cable. The SMARTprofile™ is composed of two separate strain-temperature sensor pairs, S1-T1 and S2-T2. The strain sensors are embedded in a polyethylene (PE) thermoplastic jacket such that any external force to the jacket fully transfers to the fiber optic sensors. Temperature sensors are placed in a tube before embedding in the PE jacket to provide a strain-free condition.

3. From field to laboratory

The motivation to initiate this laboratory program came from an initial field installation in 2011.[24] Five SMARTprofiles™ were installed across a 1000 m deep, 25 m high sill pillar. Boreholes breaking through the pillar allowed access from sides of the pillar. Only five stopes of the pillar, which was in early stages of extraction, were mined out during

Table 1
DiTeSt™ configuration used in the measurements.

Spatial resolution	Sampling interval	Distance resolution	Frequency resolution	Frequency swap range
0.5 m	0.1 m	0.1 m	1 MHz	10.2–11.1 GHz