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Investigating the Effect of Contributory Factors on the Response of Fibre Optic Cable for Underground Monitoring of Geological Stress in British Columbia

S. Hendi[1], Department of Earth, Ocean and Atmospheric Sciences, The University of British Columbia, Vancouver, British Columbia, shendi@eoas.ubc.ca

E. Eberhardt, Department of Earth, Ocean and Atmospheric Sciences, The University of British Columbia, Vancouver, British Columbia

M. Gorjian, Department of Earth, Ocean and Atmospheric Sciences, The University of British Columbia, Vancouver, British Columbia

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Introduction

In situ stress is one of the most important boundary conditions in rock-engineering design. It dictates many important design decisions, such as the optimal orientation of horizontal boreholes for energy-development projects (geothermal, oil, gas), as well as the orientation, dimensioning and support design of underground excavations for mining and hydroelectric power infrastructure to ensure stable and safe excavations. However, it is extremely difficult to measure ground stress reliably, resulting in significant uncertainty for, and risk to, these projects. This frequently leads to less than optimum design performance and costly mistakes that, on some projects, represent lost value in the range of tens of millions of dollars.

Despite its importance, it is also the most challenging characteristic to accurately assess in rock-engineering design. As a result, a variety of strategies have been developed, each with its own set of limits and difficulties concerning their reliability (Amadei and Stephansson, 1997; Haimson and Cornet, 2003; Sjöberg and Klasson, 2003):

- most involve point measurements, giving rise to uncertainty owing to geological heterogeneity
- many are destructive, limiting testing to a single measurement, or cause unwanted permanent change to the rock
- most involve a higher per measurement cost.

The emergence of fibre-optic sensing capabilities offers several advantages that can potentially overcome existing challenges. The use of fibre optics in stress-measurement techniques is leading to the development of a nondestructive approach capable of monitoring both in situ stress states as well as any subsequent stress changes in response to engineering activities (e.g., mining). In addition, this technique can also be used to measure the stress state away from a borehole, as well as along the length of the borehole, while being lower cost compared to conventional methods. To use fibre optics in the development of a stress-measurement technique, it is crucial to consider contributory elements that play a critical part in the response of optical fibre sensors. Prior to this work, no attempt to use a fibre-optic cable to measure geological in situ stresses had been undertaken successfully. The aim of this study is to investigate the influence of three different borehole-filling materials and of changes in borehole diameter on a fibre-optic system measuring geological stress.

Distributed Acoustic Sensing

Fibre-optic cable exhibits three scattering mechanisms: Raman, Brillouin and Rayleigh scattering. Since Rayleigh scattering is intrinsically independent of any external fields that may affect the surrounding environment, it is considered a direct-sensing mechanism, as opposed to Raman and Brillouin scattering. Rayleigh scattering is being used in this study to estimate in situ stresses caused by seismic waves propagating in the rock.

Rayleigh-scattering–based, distributed acoustic sensing (DAS) systems could transform a fibre-optic cable into a sensor array, allowing users to detect and monitor many physical factors, such as temperature, vibration and strain, over a long distance, with precise spatial and temporal precision. The DAS system has been developed for a variety of applications, each with different spatial resolutions, spectral ranges and sensing ranges (Bakku, 2015; Miah and Potter, 2017).

A typical DAS system consists of a surface-mounted interrogator unit (IU) coupled to a fibre-optic connection. To

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measure strain in different parts of the fibre, the IU transmits short laser pulses into the fibre and analyses the backscattered energy using optical time-domain reflectometry (OTDR) or optical frequency-domain reflectometry (OFDR). Under the same environmental conditions, the OFDR mode exhibits more sensitivity than the well-known OTDR. The optical power required from the necessary light source for OFDR is lower for the same dynamic range and OFDR successfully exceeds the spatial resolution and signal-to-noise ratio dynamic range of OTDR. In the OFDR system, the source is swept over a certain frequency, but the amplitude is kept virtually constant. Because of the limitations imposed by the sample size as well as the advantages of OFDR over OTDR (e.g., higher spatial resolution), an IU system based on OFDR was used in this research (Hartog, 2017).

Each fibre-optic section serves as a single-component seismic sensor, measuring the axial strain generated by a seismic wave in the optical fibre. One disadvantage of fibre optics is its low broadside sensitivity. As mentioned in Mateeva et al. (2014), applying the DAS technique using a straight fibre-optic cable revealed a directional sensitivity limitation; this limitation is manifested by a reduced sensitivity to broadside waves, or waves that travel perpendicular to the fibre. According to Den Boer et al. (2016), to improve sensitivity on the broadside, a fibre should be wrapped around a mandrel core at a predetermined wrapping angle (α).

Over the past few decades, fibre-optic DAS has been used in numerous settings such as the oil and gas industry as well as mining, civil and environmental engineering due to its capacity to work in confined spaces, measure various parameters over long distances, operate at low-power requirements, withstand harsh environments (high temperature and pressure) and protect itself from potential electromagnetic interference (Nath et al., 2006; Naruse et al., 2007; Molenaar et al., 2012; Kamal, 2014; Mateeva et al., 2014; Miller et al., 2016; Zhao et al., 2016; Zhou et al., 2019). One of the planned outcomes of this extensive research is to develop a stress-measurement technique based on the fibre-optic cable. The emergence of fibre-optic sensing capabilities offers several advantages that can not only help overcome the challenges posed by the currently available techniques but also:

- provide both stress magnitude and orientation in one measurement (other techniques require multiple measurements)
- provide a nondestructive measurement technique (i.e., measurements can be repeated for added precision and confidence)
- be used to measure the stress state of large volumes of rock (i.e., less likely to provide misleading measurements due to heterogeneity)
- be used to measure stress profiles along the borehole and, through repeat surveys, stress changes.

Method

The goal of this study is to investigate the response of helically wound cable (HWC) fibre to three different types of borehole-filling material (cement, polymer-based mud and invert-emulsion mud) and to changes in the borehole diameter. The combination of two distinct analytical methods was used to stimulate the response of fibre-optic cable. By assuming a plane wave travelling through a multilayered media in 2.5 dimensions (Figure 1), it is possible to calculate dynamic strains in the vertical and radial directions as a function of the angle of incidence using this integrated technique (Kuvshinov, 2016; Hendi et al., 2020b).

The first method, presented in Hendi et al. (2020b), is used to calculate the cable's axial strain. The second approach, outlined in Kuvshinov (2016), is applied to calculate the radial strain using the axial strain established in the previous

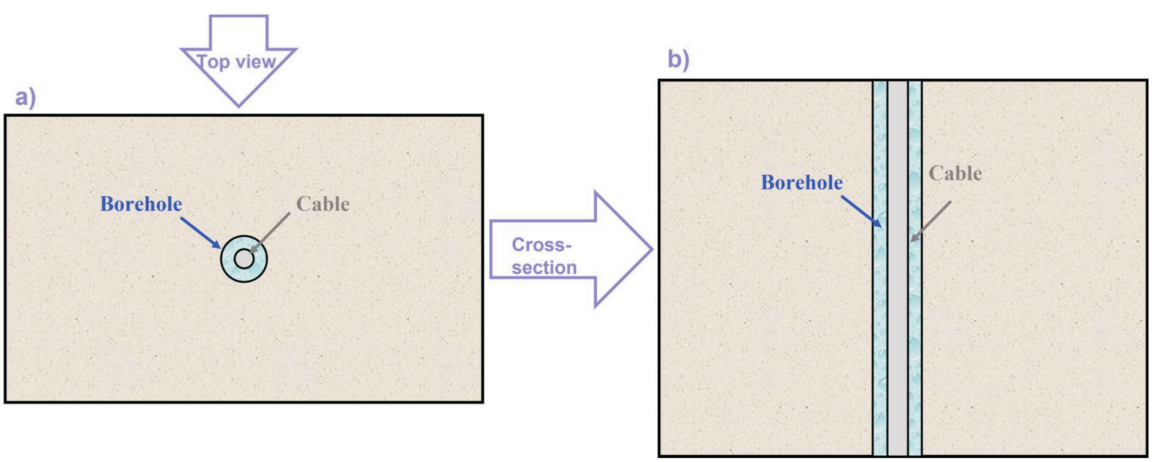

Figure 1. Depiction of the top view and cross-section of the geometry used in different borehole-filling–material scenarios. **a)** A helically wound cable is positioned inside a borehole filled with any of three filling materials. **b)** The diameter of a cement-filled borehole can be modified to examine how the change influences cable-fibre reaction.

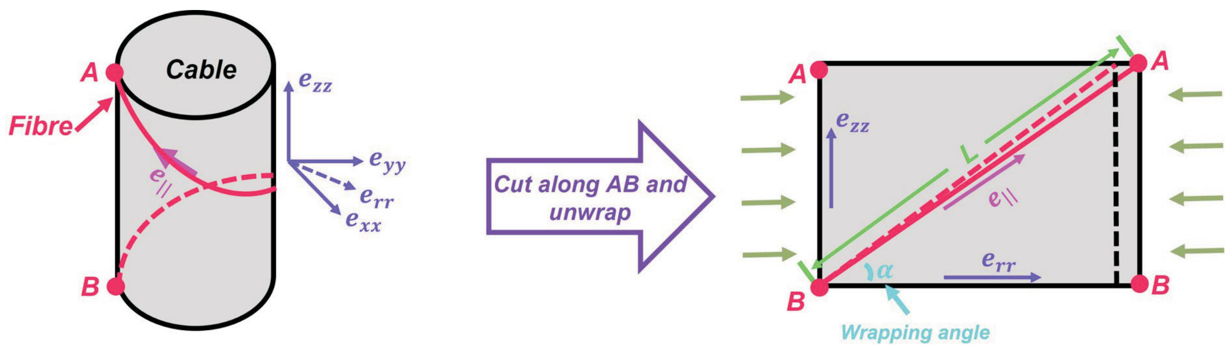

Figure 2. Demonstration of the wrapping angle (α) of helically wound cable (HWC). If the cylindrical surface of a cable (grey) was sliced along AB and unwrapped to a horizontal plane, the fibre trajectory would be represented by the diagonal red line visible in the panel on the right. The wrapping angle (α) is the angle produced by the circumference of the cable and the fibre (BB); the direction of the strain (e) is expressed as being radial ($_{rr}$), axial ($_{zz}$), or occurring in the y-axis ($_{yy}$) or x-axis ($_{xx}$) plane. When a wave strikes the HWC, the cable (dashed black line) deforms and the fibre (red dashed line) deforms as well (after Hornman, 2017).

step. Equation 1 relates the axial and radial strains to the strain of the HWC (Figure 2):

$$e_{ll\,(fibre)} = e_{zz\,(cable)} \cos^2\alpha + e_{rr\,(cable)} \sin^2\alpha \quad (1)$$

where e represents strain along the fibre ($_{fibre}$), axial strain in the cable ($_{zz[cable]}$) and radial strain in the cable ($_{rr[cable]}$), respectively, and α represents the wrapping angle of the fibre around the cable.

Two assumptions have been made in this analytical simulation. Firstly, a point source is assumed to be a specific distance away; as a result, the spherical wave can be simplified to a perfect plane wave, with the strains all occurring in the same plane. Secondly, the dominant frequency and amplitude of the point source are 8 kHz and 1 Pa, respectively.

Based on the foregoing, four borehole-filling–material scenarios were developed:

- Scenario 1: a HWC cable is placed in the middle of a cement-filled borehole (Figure 3). To determine how the cement's properties should be defined to obtain an optimum response from the HWC cable, the lower Young's modulus (associated with softer material) of the cement is changed to the higher modulus associated with the surrounding rock (considered as hard cement).

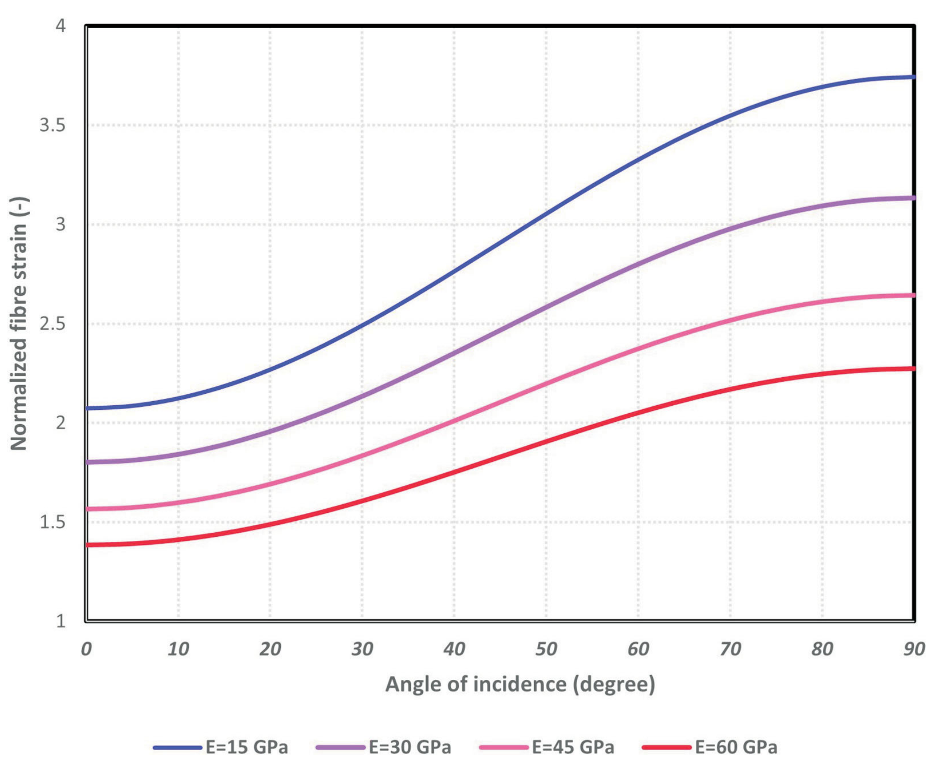

Figure 3. Effect of the properties of cement-filled boreholes (Young's modulus [E]) on the response of helically wound cable as a function of the angle of incidence (scenario 1).

- Scenario 2: a HWC cable is placed in the middle of a mud-filled borehole (Figure 4). To determine how the mud's properties should be defined to obtain an optimum response from the HWC cable, two common types of muds frequently used in industry are used to fill the borehole: polymer-based mud and invert-emulsion mud (mud properties from Hendi et al., 2020a).
- Scenario 3: a HWC cable is placed in the middle of a cement-filled borehole (Figure 5). The diameter of the borehole is altered to examine the sensitivity of HWC-fibre response as a function of borehole diameter.
- Scenario 4: The findings from scenarios 1 and 2 are combined to determine which combination of borehole-filling material and HWC cable is the most efficient. The response of a HWC cable inserted in a borehole, which in one case is filled with hard cement (Young's modulus equivalent to that of the surrounding rock) and, in another, with dense polymer-based mud, is compared (Figure 6).

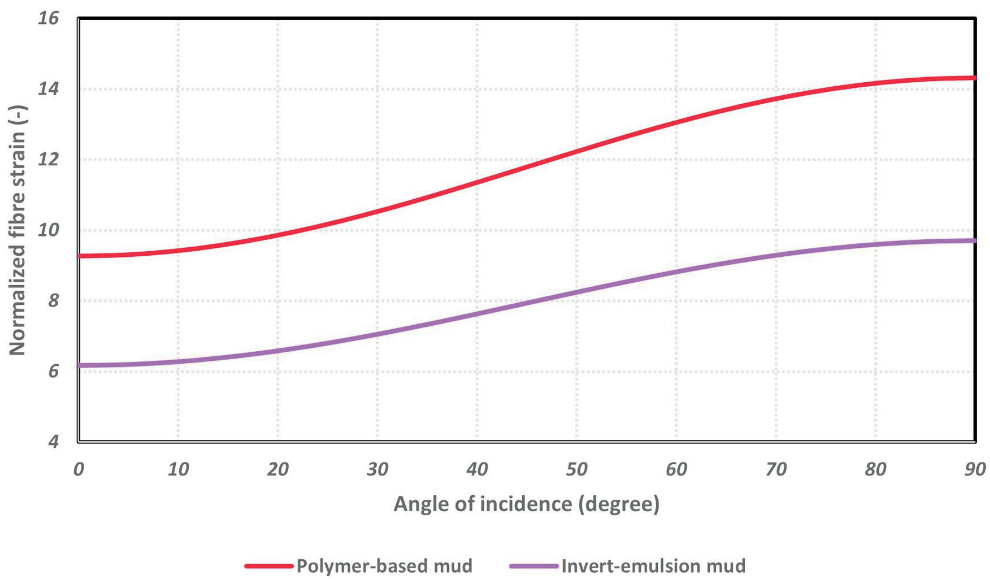

Figure 4. Effect of the properties of mud-filled boreholes on the response of helically wound cable as a function of the angle of incidence (scenario 2).

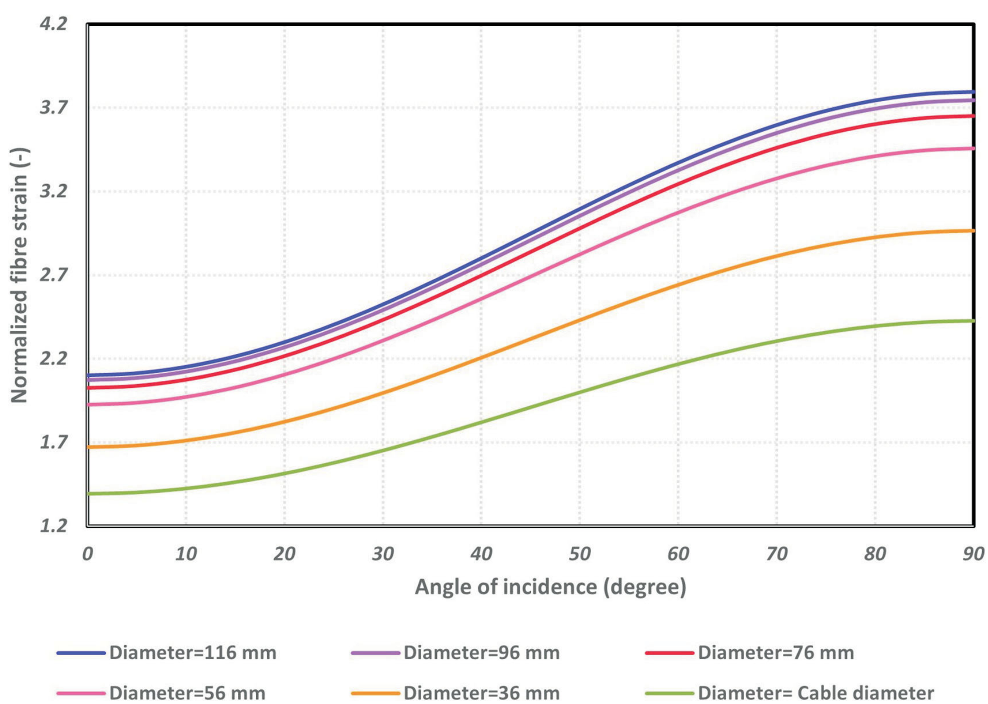

Figure 5. Effect of changes to borehole diameter on the response of helically wound cable as a function of the angle of incidence (scenario 3).

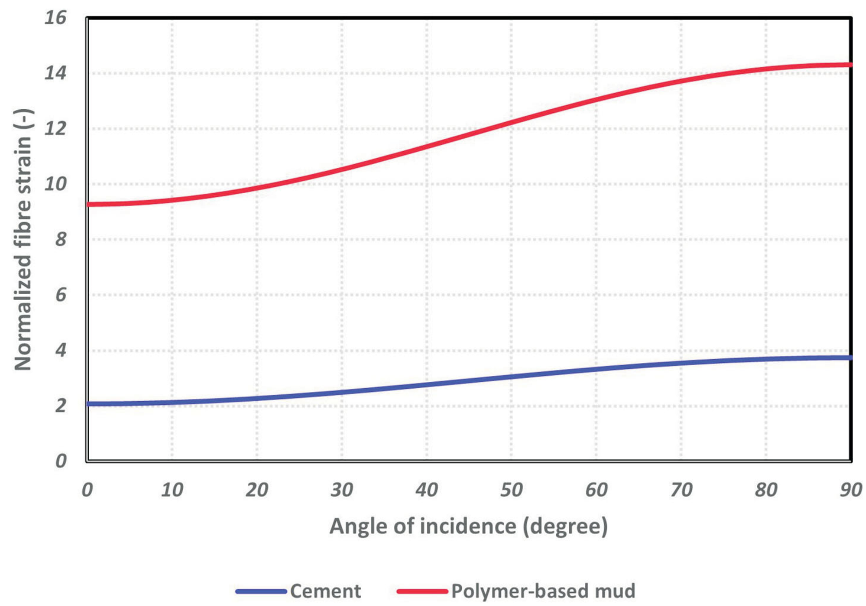

Figure 6. Comparison between the effect of polymer-based mud and cement used as borehole-filling material on the response of helically wound cable fibre.

Tables 1 and 2 show the geometry and characteristics of the materials for the various borehole-filling–material scenarios, respectively (values taken from Hendi et al., 2020a, b).

Results and Discussion

Figures 3 to 5 illustrate the strain distributions computed using the combined analytical technique for scenarios 1 to 3. A comparison of polymer-based mud- and cement-filled boreholes is shown in Figure 6. In all scenarios, the sensitivity of the HWC increases as the angle of incidence increases.

Table 1. Geometric parameters used in analytical stimulation of the response of fibre-optic cable. The cable and borehole diameters are determined using common values found in the field. In this study, the rock formation is assumed to stretch to infinity in both width and height.

Geometric parameters			
Scenario	1	2	3
Borehole diameter (mm)	116	116	25 (cable size)–116
Borehole height (m)	2	2	2
Cable diameter (mm)	25	25	25
Cable length (m)	0.5	0.5	0.5
Formation diameter (mm)	2	2	2
Formation length (m)	2	2	2

Scenario 1

The results of scenario 1 help in determining how cement properties should be designed to obtain the optimum response from HWC. The Young's modulus of the cement has been changed in this scenario from one associated with soft material to one with properties nearer those of the surrounding rock. The results of this study show that, as the layer properties of the cement (Table 1) surrounding the cable near those of the rock formation, the performance of the HWC fibre decreases (Figure 3).

Scenario 2

The results of scenario 2 reveal more about how mud qualities affect HWC optimum response at different angles of incidence. Two common types of mud used frequently in industry (polymer-based mud and invert-emulsion mud) were considered in this scenario and their respective effects are depicted in Figure 4. The results showed that the HWC fibre performed better in the denser polymer-based mud.

Table 2. Layer (domain) properties used for modelling of the response of helically wound cable to different borehole-filling materials and changes in borehole diameter (values from Hendi et al, 2020a, b).

Material	Density (ρ) (kg/m^3)	Compressional velocity (Vp) (m/s)	Young's modulus (E) (GPa)	Poisson's ratio (v) (-)
Rock formation	2734	5736	60	0.28
Cable	1200	1183	1.6	0.15
Cement	2240	2728	15-60	0.2
Invert-emulsion mud	1570	1540	-	-
Polymer-based mud	1830	2350	-	-

Scenario 3

In scenario 3, the impact of borehole diameter on the HWC response in the case of a hard cement-filled borehole (Young's modulus equivalent to that of the surrounding rock) was investigated. In this scenario, boreholes of various diameters were used, varying between 116 mm and 25 mm (i.e., equal to the diameter of the cable; Figure 5). The results indicate that a larger borehole diameter results in better performance of the HWC optical fibre. Responses increase significantly when the borehole diameter is nearly double that of the optic-fibre cable; after that point, borehole diameter has a less significant impact on fibre-optic cable response.

Scenario 4

The performance of HWC fibre was also investigated as a function of surrounding material (cement vs polymer-based mud; Figure 6). Theoretical results indicate that the HWC fibre performs better in polymer-based mud than cement.

Conclusion

Using an integrated analytical technique, strain values in helically wound fibre-optic cable were calculated for three scenarios representing realistic situations, based on the effects of the borehole-filling material and change in borehole diameter on the axial and radial strains of the HWC. The results of this analysis reveal that HWC fibre performs better when the Young's modulus of the cement filling the borehole is low (indicating material softer than the surrounding rock formation). In the case of boreholes filled with polymer-based mud, the performance of the HWC fibre is far higher compared to that achieved using invert-emulsion mud. When HWC is embedded in the denser polymer-based mud, it has a higher sensitivity than when it is embedded in cement. The diameter of the borehole and the sensitivity of the HWC share a direct relationship: when the borehole diameter is approximately two times that of the cable, HWC sensitivity reaches its maximum.

The findings of this study can be considered one of the primary steps in the development of a stress-measurement technique based on fibre-optic cable, which allows for improved precision and accuracy in recording results. By employing stress-measuring techniques, British Columbia mining firms may see a boost in production, while reducing the number of instability events and therefore improving mine safety.

Future Research Directions

The results of this study will be used to build a bench-top experiment to stimulate fibre-optic cable response under simulated field conditions to estimate in situ stresses. The findings will be used as a guideline for installing distributed fibre-optic cable and improving its overall performance. This work will be undertaken in January 2022 and final results published as part of the lead author's doctoral thesis in 2024.

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