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Development and testing of the CMIN-BCM for monitoring borehole closure in underground environments

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ABSTRACT

Monitoring borehole deformation during underground excavation activities is one method of evaluating rock mass performance during mining and tunneling. Continued monitoring and comparison to anticipated rock mass behaviour and/or existing stress models are important components of the engineering design and verification process. A comprehensive monitoring program provides real-time feedback of in situ rock behavior and delivers an added level of safety monitoring for underground works. Furthermore, accurate monitoring of borehole deformation can also be used to estimate changes to the induced stress field, and in turn, potential back analysis of the far field stress regime. CanmetMINING has developed a robust tool, referred to as the CanmetMINING Borehole Closure Meter (CMIN-BCM), for accurate and precise measurement of borehole deformation. The instrument, designed for use in 60 mm diameter boreholes, has a maximum range of 6.0 mm, resolution of 0.05 µm and accuracy of 5 µm over its full range. This paper presents a summary of instrument development and its specifications, as well as the results of bench scale and rock block laboratory testing. Future testing and development of the instrument will include a field testing program, including underground installation to monitor in situ conditions, as well as modifications to the external components of the instrument to increase its ability to withstand harsh field conditions.

RÉSUMÉ

Le suivi de la déformation des forages durant les activités d'excavation est une façon d'évaluer le comportement du roc lors du minage ou du creusement de tunnels. Le suivi en continu et la comparaison des observations au comportement anticipé pour le roc et/ou aux modèles de calcul existants sont d'importances composantes du processus de conception et de vérification en ingénierie. Un programme de suivi complet procure une évaluation en temps réel du comportement in situ des ouvrages et ajoute au degré de sécurité des travaux souterrains. Plus encore, un suivi rigoureux de la déformation des forages peut également être utilisé pour estimer les variations induites au champ de contrainte, et inversement, lors d'une éventuelle rétro-analyse du régime de contrainte à grande échelle. CanmetMINES a développé un outil robuste appelé senseur de déformation des forages CanmetMINES (CMIN-BCM), pour mesurer de façon juste et précise la déformation des forages. L'instrument conçu pour utilisation à l'intérieur de forages de 60 mm de diamètre possède une course maximale de 6.0 mm, une résolution de 0.05 µm et une précision de 5 µm en pleine extension. Cet article présente un sommaire du développement de l'instrument et ses spécifications, de même que les résultats des essais de vérification réalisés en laboratoire à l'intérieur de blocs de roche et d'autres dispositifs de chargement. Les essais à venir et le développement de l'instrument incluront la réalisation d'un programme d'essai en chantier, notamment l'installation du senseur dans un site souterrain pour suivre les conditions en place, de même que les modifications à apporter à l'instrument afin de résister aux conditions adverses habituellement rencontrées en chantier.

1 INTRODUCTION

Monitoring stress changes during underground and/or civil engineering works such as mines and tunnels is an important indicator of in situ rock mass behaviour. Continued monitoring during excavation progression is part of the iterative design process, where monitoring results provide in situ data to mining and geotechnical engineers to assess the observed versus predicted behaviour of a rock mass. Results of observed rock mass behaviour can be incorporated into numerical models (i.e. back-analysis of observed deformation) to refine the engineering design of an excavation, as needed. This may include modifications to excavation geometry and/or changes in ground support design.

While stress is not directly measured per se, there are a variety of instruments and sensors that measure strain or deformation, which combined with an accurate understanding of the intact rock and rock mass elastic properties can be used to estimate stress change (Dunnicliff, 1993). A description of in situ stress measurement techniques and methods of monitoring stress change are well summarized in the International Society for Rock Mechanics (ISRM) Suggested Methods for Stress Estimation (Parts 1 to 5) (Hudson et al., 2003; Sjoberg et al, 2003; Haimson and Cornet, 2003; Christiansson and Hudson, 2003; Stephansson and Zang, 2012), as well as in Amadei and Stephansson (1997) and Zang and Stephansson (2010).

Stress change(s) can either be estimated by interpreting absolute stress conditions at two discrete time intervals, or through longer-term continued monitoring to determine changes in relative stress conditions. CanmetMINING's Borehole Closure Meter (CMIN-BCM) has been developed as an instrument to monitor borehole deformation over time for the purpose of estimating a relative change in stress conditions. Development of the CMIN-BCM is a continuation of work initiated within

CanmetMINING's Rock Mechanics Laboratory in Ottawa, Ontario to investigate the behaviour of highly-stressed rock structure within deep underground mines.

Initially conceived as an instrument to monitor large displacements in soft rock mining environments (such as salt, potash or coal), the CMIN-BCM has been tested in the laboratory using intermediate strength rocks undergoing moderate displacement within the elastic range. By testing the CMIN-BCM in rock blocks within the elastic range the results can be more easily compared to simple analytical solutions, although the high resolution, high precision and relatively large range of the sensor make it potentially suitable for both hard or soft rock environments.

This paper presents the laboratory testing results of the instrument in boreholes drilled in a series of rock blocks, and the comparison of these results to the calculated values from stress-deformation theory, as well as estimated deformation results from representative two-dimensional finite element models.

2 CMIN-BCM DESIGN AND CALIBRATION

2.1 Design and Specifications

The CMIN-BCM has undergone several revisions to improve the range, accuracy and precision of the instrument during the course of its development. The results presented herein represent the most recent iteration of the instrument (version 10), which is essentially a stainless steel spring-loaded caliper, with a very low stiffness such that it can be classified as a soft-inclusion type cell. The current design uses a spring with a stiffness of 200 lb/in (22 N/m) housed between two stainless steel shoes. A laser displacement sensor precisely measures closure or dilation of the caliper. The CMIN-BCM is designed for use in 60 mm (+/-) diameter boreholes and is installed by seating the instrument at the desired orientation in a borehole and sliding the wedge along the upper shoe until the tool is stable in the borehole. The wedge and lower shoe, which are in contact with the borehole wall, have curved surfaces to minimize induced stress concentrations and/or damage to the borehole wall from the instrument. The CMIN-BCM is shown in Figure 1, with key components of the instrument identified.

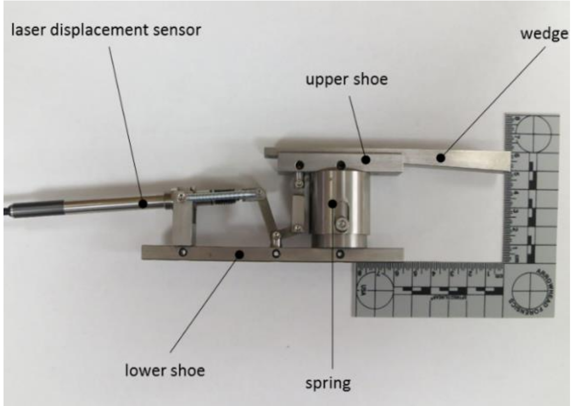

Figure 1. Photograph showing key components of the CMIN-BCM (version 10).

The CMIN-BCM has a maximum range of 6.0 mm, capable of reporting 0-10% strain in a nominal 60 mm diameter borehole. The instrument resolution is 0.00005 mm (0.05 µm), and the theoretical accuracy is 0.0005 mm (0.5 µm). Vertical displacement of the caliper is approximately 0.5 times the horizontal displacement of the laser sensor; therefore, 0.5 µm borehole closure (measured by the caliper) results in a 1 µm response in the sensor. The result is a 2-fold increase in CMIN-BCM resolution and accuracy relative to the displacement sensor used within the instrument.

The current version of the CMIN-BCM is designed to accurately measure deformation in one axis of the borehole; however, multiple instruments could be placed in series to monitor strain in multiple orientations (i.e. 0, 45, and 90 degrees) to resolve the biaxial stress conditions in the plane perpendicular to the borehole axis. Future iterations of the CMIN-BCM will attempt to incorporate measurements in different orientations within one sensor.

2.2 Instrument Calibration and Testing

A bench-scale laboratory testing program has been completed to calibrate the measured response of the laser displacement sensor to the closure or dilation experienced by the CMIN-BCM instrument. Furthermore, several controlled tests have been completed to evaluate the measurement characteristics of the CMIN-BCM (i.e. hysteresis and creep) prior to lab testing within a borehole drilled in sample rock blocks. The following sections describe the instrument calibration process and results.

2.2.1 Laser Displacement Sensor

Borehole deformation is measured by a commercially available Keyence contact laser displacement sensor (model GT-2), housed in the stainless steel caliper. As such, accuracy and precision of the laser sensor is the primary control on the accuracy and precision of the CMIN-BCM instrument. The manufacturer specifications for the Keyence GT-2 sensors include the following (Keyence, 2017):

- Measuring range = 12 mm
- Resolution = 0.1 µm (0.0001 mm)
- Accuracy = 1 µm (0.001 mm)
- Sampling interval = 4 ms (0.004 s)

The laser displacement sensors were independently tested in the laboratory using a calibrated set of gauge blocks and the results were consistent with manufacturer's specifications for sensor accuracy. The testing was completed using several sized gauge blocks and with multiple Keyence sensors and confirmed accuracy and precision of the sensor.

2.2.2 Full Range Calibration of the CMIN-BCM

Instrument calibration was completed by placing the CMIN-BCM in a vise, with a second laser displacement sensor measuring the same distance of the vise opening. The instrument was seated in the vise, extended to its maximum range, and then subjected to one cycle of compression and unloading, while continually monitoring the distance of the vise opening. The output of the CMIN-BCM was then compared to the measured closure using the displacement sensor over the full 6.0 mm range of the instrument to determine the relationship between instrument output and distance (i.e. borehole diameter). The calibration setup and calibration results are shown in Figures 2 and 3, respectively.

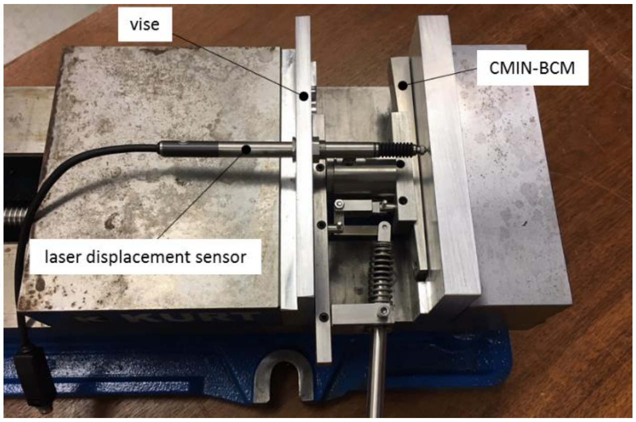

Figure 2. Calibration set up showing the CMIN-BCM in the vise with a second laser displacement sensor to measure the change in distance between the plates of the vise.

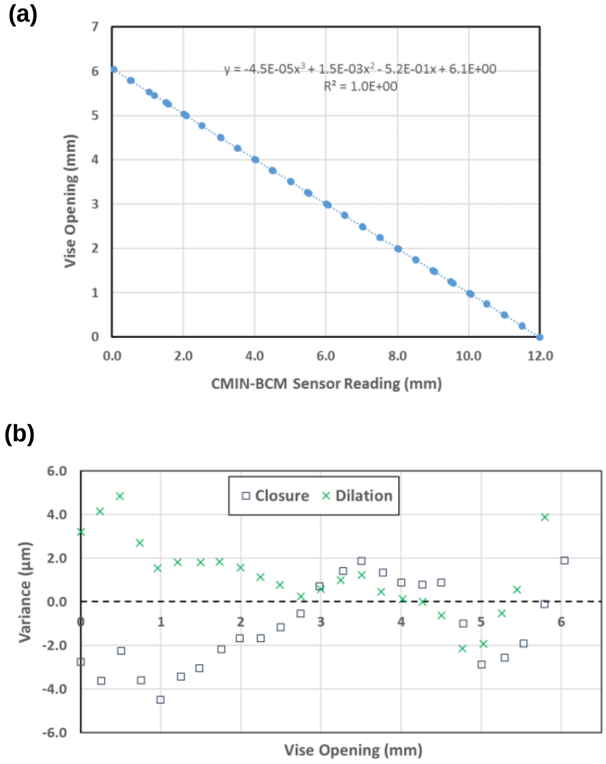

Figure 3. Results of full range CMIN-BCM calibration: (a) best fit, third order relationship between CMIN-BCM sensor reading and vise opening (i.e. borehole diameter), and (b) variance from the best fit calibration line over the full closure range.

The results of the full range calibration of the CMIN-BCM represent the most conservative assessment of instrument resolution and accuracy. A third order fit was interpreted from the calibration data, with a standard deviation of 0.0022 mm and a maximum variance of 0.0048 mm. The relationship between sensor reading/output, *R*, and opening diameter, *D* (in mm), is as follows (Eq. 1):

$$D = (-4.5\text{x}10^{-5})R^3 + (1.5\text{x}10^{-3})R^2 - 0.52R + 6.1 \qquad [1]$$

This represents the calibration fit over the entire range of the instrument. While this relationship can be used for all applications, it is recommended that the CMIN-BCM be calibrated for the anticipated range of deformation.

2.2.3 Long-term Creep Test

A longer term test of the CMIN-BCM was conducted in the laboratory to monitor instrument drift (creep). A thermistor was installed for the duration of the test to isolate the effects of thermal expansion and contraction of the vise and/or stainless steel components of the CMIN-BCM on any observed changes in closure. During the test period, the following data was recorded at 10 minute intervals: CMIN-BCM closure, laser displacement sensor reading (i.e. vise closure) and temperature. The CMIN-BCM output was corrected using Equation 1 to compare to vise closure recorded by the laser displacement sensor. Results of the creep test are illustrated in Figure 4.

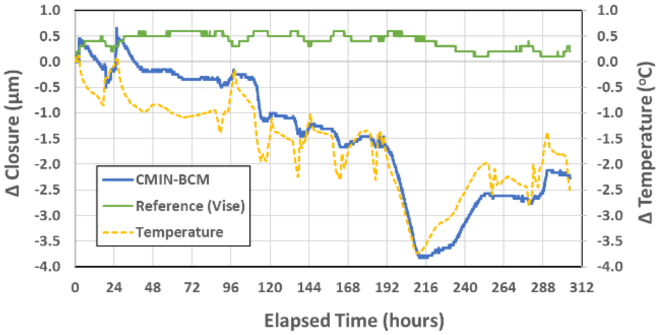

Figure 4. Test results over a 13 day period showing the change in CMIN-BCM measurement, reference vise opening (measured using the laser displacement sensor) and room temperature.

The total duration of the creep test was 305 hours (~13 days), during which time the CMIN-BCM reading fluctuated a maximum of 3.8 µm from the initial closure reading (i.e. diameter) at time = 0. During the test, drift in the reference sensor fluctuated less than 1 µm. As illustrated in Figure 4, changes in apparent closure measured by the CMIN-BCM are closely related to changes in ambient air temperature in the laboratory, although temperature changes do not seem to significantly impact the reference vise opening. It is anticipated that the CMIN-BCM, when installed in an underground environment, will undergo minimal temperature fluctuations. Therefore, thermal expansion effects of the rock and the stainless steel instrument, and the interaction between them, will not have a significant effect on borehole closure measurements.

2.3 Installation Procedure

Installation of the sensor is completed by pre-loading the spring using the wedge to match the expected conditions in the orientation of interest (i.e. borehole closure or dilation); therefore, a portion of the maximum range of the instrument is used during the installation process. Ideally, an understanding of the likely orientation of compression and dilation of the borehole axes will be known prior to installation such that the degree of preloading of the caliper/spring can reflect the direction of caliper movement. For example, when the CMIN-BCM is oriented in the axis of likely compression, minimal pre-loading of the instrument is necessary and the operational range should be close to the maximum range of the caliper. Where the instrument is oriented in the direction of maximum borehole extension, the pre-loading will be greater such that it is capable of accommodating extension.

The instrument is water resistant and made of durable materials; however, it is recognized that future development of the tool will require additional measures to increase its ability to withstand long-term use in underground conditions and in water-filled boreholes.

3 LABORATORY TESTING PROGRAM

Laboratory testing of the CMIN-BCM has been completed in the CanmetMINING Rock Mechanics Lab to simulate performance of the instrument in rock. Four test blocks were included in the testing program to simulate different borehole responses to external stress changes. The tested rock types are characteristic of intermediate strength rocks, which undergo brittle failure at low confinement and plastic deformation at higher confinement.

3.1 Specimen Selection and Preparation

Sample blocks were carefully prepared with orthogonal and parallel faces, with dimensions summarized in Table 1. A 58.8 mm diameter borehole was advanced through the centre of each block to permit installation of the CMIN-BCM. With the exception of IBL-1, which includes some visible bedding planes, the rock types are relatively homogeneous and isotropic.

Table 1. Test block rock types and dimensions.

Sample ID	Rock Type	Height (mm)	Width (mm)	Thickness (mm)
IBL-1	Indiana Buff Limestone	325.98	209.86	156.38
SCS-1	St.-Canut Potsdam Sandstone	304.48	263.50	137.46
SGG-2	Stanstead Grey Granite	336.21	260.72	132.31
OWM-2	Danby Olympia White Marble	310.26	196.88	160.22

3.2 Material Properties

Comprehensive laboratory testing was previously completed on representative intact rock samples of the Indiana Buff Limestone (IBL), Stanstead Grey Granite (SGG) and Danby Olympia White Marble (OWM) to obtain a full set of physical and mechanical properties for each block used in the testing (Labrie, 2017). Additional testing and characterization of intact rock core samples of the Saint-Canut Sandstone (SCS) was completed to establish material properties in support of the current study.

All intact rock testing was completed using a MTS Rock Mechanics Testing System, Model 815 using servo-controlled modules for axial loading and triaxial confinement. Additional details on the equipment and intact rock testing procedures can be found in Labrie (2017). A summary of the material properties derived from testing intact rock core samples is provided in Table 2.

Table 2. Physical and mechanical properties of intact rock material.

Property	Rock Type			
	IBL-1	SCS-1	SGG-2	OWM-2
Dry Density (g/cm3)	2.33	2.56	2.67	2.71
Tensile Strength (MPa)	6.95	14.08	7.03	7.91
Unconfined Strength (MPa)	55.34	173.22	130.74	54.42
Young’s modulus (GPa)	32.23	42.89	42.64	44.68
Poisson’s ratio	0.302	0.374	0.369	0.366

It should be noted the geomechanical properties of the test blocks have been estimated based on the results of intact rock core testing conducted as part of this study, and from previous laboratory studies (Labrie, 2017). Testing of SGG, IBL and OWM by Labrie (2017) included a comparison of physical properties based on testing of 44, 63, 81 and 99 mm diameter core samples and concluded that there was minimal scale effects observed, likely due to their relatively homogeneous texture and fabric. As such, for the purpose of calculating and modelling approximate borehole deformation, it is reasonable to estimate the rock test block properties using intact rock sample properties.

3.3 Equipment and CMIN-BCM Test Set-up

The CMIN-BCM was installed and independently tested in the vertical direction (i.e. 0 degrees to the loading direction, σ_1) and in the horizontal direction (i.e. 90 degrees to σ_1), to measure the maximum compressive deformation and maximum elongation of the borehole, respectively. The equipment and testing setup is shown in Figure 5 with the instrument oriented in the vertical direction.

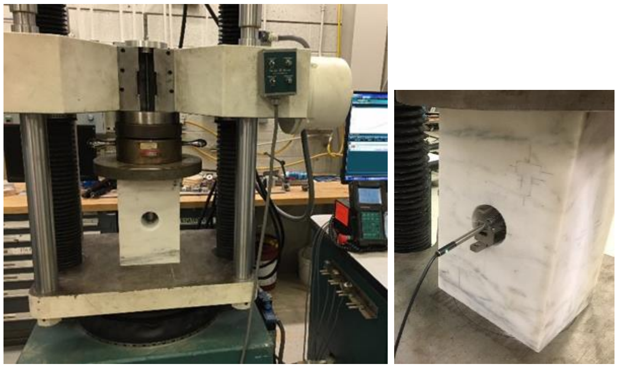

Figure 5. Equipment and test setup (OWM-2) with the CMIN-BCM installed vertical (i.e. in the loading direction). Setup in the load frame (left) and caliper placement in the borehole (right).

The CMIN-BCM was calibrated over a 0.3 mm range, representing 0.5% strain in a nominal 60 mm diameter borehole for the purpose of testing the functionality in test blocks. This range, while significantly less than the maximum range of the instrument, represents the anticipated deformation within the elastic range of the rock material used as the test block media. Calibration over a narrow range allows for increased accuracy and precision of the CMIN-BCM, and in practice, the instrument should be calibrated over the anticipated range of deformation.

Testing was completed using a servo-controlled Tinius-Olson load frame with a maximum capacity of 530 kN. Blocks were loaded vertically to a maximum of 500 kN for each test. The loading sequence included three stages: 1) increasing load at a constant rate of 0.5 kN per second 500 kN; 2) maintenance of the maximum load (+/- 1.0 kN) for 1000 to 1800 seconds; and 3) removing the load at a constant rate of 0.5 kN to the end of the test. The applied stresses to each test block are summarized in Table 3.

Table 3. Maximum applied stress to each test block

Test Block	Applied Stress (MPa)
IBL-1	14.9[a] / 15.2[b]
SCS-1	13.8
SGG-2	14.5
OWM-2	15.9

Notes: a – CMIN-BCM oriented vertically
b – CMIN-BCM oriented horizontally

Two cycles of loading-static-unloading were applied to the IBL-1 and SCS-1 test blocks, without adjusting or repositioning the CMIN-BCM, to observe the instrument response. Only one loading-unloading cycle was completed on the remaining test blocks.

4 ESTIMATES OF BOREHOLE DEFORMATION

4.1 Analytical Method

Borehole deformation in a homogeneous, isotropic, elastic medium can be approximated using the Kirsch solution. For a uniaxial stress field, under plane stress conditions, borehole deformation, U_d, can be determined using Equation 2, as follows (Merrill and Peterson, 1961):

$$U_d = \frac{d\sigma_1}{E}(1 + 2\cos 2\theta) \qquad [2]$$

where: U_d = change in diameter (mm)
d = original diameter of the borehole (mm)
σ_1 = applied stress (MPa)
θ = angle from σ_1 (degrees)
E = Young's modulus (MPa)

The analytical solution was used to calculate the expected borehole deformation at an angle of 0 and 90 degrees relative to the loading orientation, and is discussed in Section 5.

4.2 Numerical Modelling

A two-dimensional finite element model (FEM) was created using Rocscience RS2 (v.10.0) (Rocscience, 2019). The numerical model is another method of estimating borehole deformation of each test block for comparison to the measured deformation using the CMIN-BCM and provides a useful illustration of elastic stress concentration around a circular opening. The 2-D model, under plane strain conditions, does not account for deformation of the in-plane axis; however, for the purpose of comparing a predicted deformation against measured deformation, the 2-D FEM is considered an acceptable approximation.

Material properties were assumed to be homogeneous and isotropic, which is reasonable for the rock types tested and the models were run assuming fully elastic conditions. Vertical boundaries were free to deform in both the x- and y-direction, while the lower horizontal boundary was fixed in the y-direction. A stiff cap (200 GPa), to simulate the steel platen, was placed above the rock block. A distributed load was applied to the top of the steel platen to simulate compression on the block from the Tinus-Olsen load frame. Model setup, showing OWM-2 dimensions and boundary conditions used for each model block, as well as the induced stress conditions around the borehole (Sigma 1) are presented in Figure 6.

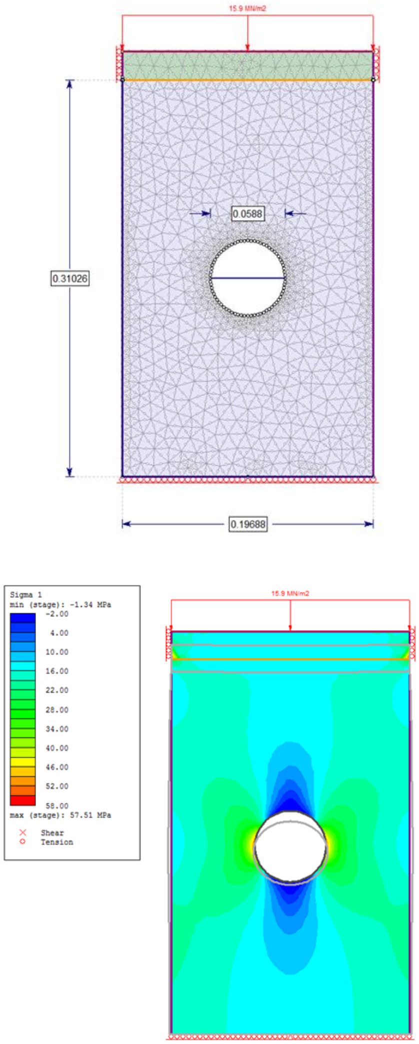

Figure 6. RS2 model setup of OWM-2 (top) and resultant stress distribution (bottom). Deformation is shown in grey and exaggerated to illustrate block deformation and borehole shape while the material is under load.

5 RESULTS AND INTERPRETATION

Borehole deformation was measured using the CMIN-BCM at one second intervals during the loading sequence for each test. Positive borehole deformation represents compression and closure in the direction of loading, in this case the vertical plane (y-axis). Negative deformation is representative of extension, occurring in the horizontal plane (x-axis).

A summary of measured borehole deformation in the vertical and horizontal axis under maximum load is presented in Table 4. Vertical borehole deformation was measured from 0.064 to 0.078 mm in the four intermediate rock test blocks. Deformation in the horizontal plane was measured between -0.019 and -0.033 mm. The similar magnitude of deformation observed between the test blocks was expected based on the similarity in elastic properties of test block materials.

Table 4. Comparison of measured deformation to analytical and modelled deformation results

Test Block	Orientation relative to σ_1	Change in BH Diameter (mm)		
		CMIN-BCM	*Analytical*	*2D FEM*
IBL-1	0	0.078	0.082	0.083
	90	-0.033	-0.028	-0.034
SCS-1	0	0.064	0.057	0.055
	90	-0.019	-0.019	-0.021
SGG-2	0	0.076	0.060	0.058
	90	-0.021	-0.021	-0.022
OWM-2	0	0.072	0.063	0.062
	90	-0.021	-0.021	-0.025

Results of the measured deformation using the CMIN-BCM presented in Table 4 compare very well to the anticipated change in borehole diameter calculated using the analytical solution and estimated using the 2-D FEM. It is worth noting that there is very strong agreement between the analytical solution and modelling result, which both incorporate the ‘known’ elastic properties of the material. Given the measured borehole deformation is highly dependent on the block elastic properties and the challenge associated with scaling intact rock properties, this result in not surprising. Furthermore, it emphasizes the importance of accurate characterization of intact rock properties and a thorough assessment of the in situ rock properties.

The rock mass modulus is often estimated from intact rock elastic modulus using the empirical relationship presented in Hoek and Diederichs (2006). However it is important to critically evaluate laboratory testing data, the influence of sampling bias, and potential site specific material properties and structural features such as veining or other material inhomogeneity’s that may influence the in situ modulus in the area surrounding a borehole. This is not a trivial exercise and is well beyond the scope of this paper, but is important to recognize that in situ material properties must be well constrained in order to estimate stress changes from deformation measurements.

6 INSTRUMENT LIMITATIONS AND UNCERTAINTY

The CMIN-BCM is currently limited to measurement of deformation in only one orientation, therefore interpretation of the biaxial stress conditions in a plane normal to the borehole axis will require a minimum of three separate sensors oriented at 0, 45 and 90 degrees. This is a clear limitation of the instrument relative to some other available gauges; however, if the intent is to monitor borehole closure/deformation for the purpose of monitoring in situ rock mass behaviour and comparison to anticipated behaviour, then interpretation of the complete stress tensor may not always be necessary. Future testing will be completed with multiple CMIN-BCMs installed in series at different orientations.

During testing, it was observed that the instrument performed better (more smoothly) when installed oriented in the direction of loading relative to in the horizontal plane. This was interpreted to be due to the relatively weak spring, which when seated in the horizontal position with the borehole undergoing vertical compression and horizontal dilation, may move slightly out of alignment at maximum extension, thus leading to potential errors in displacement during the unloading cycle. This could be overcome by using a slightly stiffer spring (while still remaining a soft enough system to act as a soft inclusion type gauge) or by increasing the pre-loading on the caliper using the wedge. In practice, it is expected that deformation will be compression or extension and not cyclical, so this may not be an important factor. However, in general it was noted during testing that proper and consistent seating of the instrument in the borehole is important to ensure accurate and repeatable results.

As noted in Section 2, the current version of the CMIN-BCM is water *resistant* and is made of durable components; however, the instrument is not suitable for use in water-filled boreholes and the long-term ability of the instrument to withstand underground conditions has not been evaluated.

7 CONCLUSIONS AND FUTURE DEVELOPMENT

The CMIN-BCM has been designed and tested in-house at CanmetMINING's Rock Mechanics Laboratory in Ottawa, Ontario. Made of durable stainless steel components, and a high resolution and high accuracy laser displacement sensor, the instrument is designed for installation in a nominal 60 mm diameter borehole. The CMIN-BCM is accurate to within +/- 5 µm, which in a 60 mm borehole represents less than 0.01% strain.

Functional and preliminary laboratory testing has been completed on this prototype and the results are encouraging. The CMIN-BCM is relatively easy to install and provides high resolution data, which is required in hard rock environments where only minimal strain is expected. Testing of the gauge within rock blocks yielded deformation results that were comparable to the analytical solution, and to modelled values.

Future testing of the CMIN-BCM is important to demonstrate that the instrument is capable of collecting data for long periods of time in an underground environment. Should field testing of the gauge be successful, enhancements to the instrument in terms of remote data logging capability and improvements to the data acquisition system will be required.

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REFERENCES

Amadei, B. and Stephansson, O. 1997. *Rock Stress and its Measurement,* 1st ed., Chapman & Hill, New York.

Christiansson, R. and Hudson, J.A. 2003. ISRM Suggested Methods for rock stress estimation – Part 4: Quality control of rock stress estimation, *International Journal of Rock Mechanics & Mining Sciences*, 40: 1021-1025.

Dunnicliff, J. 1993. *Geotechnical Instrumentation for Monitoring Field Performance*, 2nd ed., John Wiley & Sons, New York.

Haimson, B.C. and Cornet, F.H. 2003. ISRM Suggested Methods for rock stress estimation – Part 3: Hydraulic fracturing (HF) and/or hydraulic testing of pre-existing fractures (HTPF). *International Journal of Rock Mechanics & Mining Sciences*, 40: 1011-1020.

Hoek, E. and Diederichs, M.S. 2006. Empirical estimation of rock mass modulus, *International Journal of Rock Mechanics & Mining Sciences,* 43: 203-215.

Hudson, J.A., Cornet F.H. and Christiansson, R. 2003. ISRM Suggested Methods for rock stress estimation – Part 1: Strategy for rock stress estimation, *International Journal of Rock Mechanics & Mining Sciences,* 40: 991-998.

Labrie, D. 2017. Frictional properties of rocks as a function of rock type, specimen size and confining pressure, *51st US Rock Mechanics/Geomechanics Symposium*, American Rock Mechanics Association, San Francisco, USA, June 25-27, Paper 17-64: 13p.

Merrill, R.H. and Peterson, J.R. 1961. *Deformation of a borehole in rock*, Report No. 5881, U.S. Dept. of the Interior, Bureau of Mines, Washington.

Keyence, 2017. *High-accuracy Digital Contact Sensor*, GT2-70 Series Instruction Manual, Keyence Canada Inc, Mississauga (ON), Canada.

Rocscience Inc., 2019. RS2 – 2D Geotechnical Finite Element Analysis, Version 10.

Sjoberg, J., Christiansson, R. and Hudson, J.A. 2003. ISRM Suggested Methods for rock stress estimation – Part 2: Overcoring methods, *International Journal of Rock Mechanics & Mining Sciences,* 40: 999-1010.

Stephansson, O. and Zang, A. 2012. ISRM Suggested Methods for Rock Stress Estimation – Part 5: Establishing a Model for the In Situ Stress at a Given Site, *Rock Mechanics and Rock Engineering*, 45: 955-969

Zang, A. and Stephansson, O. 2010. *Stress Field of the Earth's Crust*, Springer, New York, USA.