Resource Operators Conference

Faculty of Engineering and Information Sciences

2022

Development of a wireless system to measure the strain/deformation of rock bolts

Hadi Nourizadeh

Ali Mirzaghorbanali

Naj Aziz

Kevin McDougall

Ali Akbar Sahebi

DEVELOPMENT OF A WIRELESS SYSTEM TO MEASURE THE STRAIN/DEFORMATION OF ROCK BOLTS

Hadi Nourizadeh[1], Ali Mirzaghorbanali[2], Naj Aziz[3], Kevin McDougall[4] and Ali Akbar Sahebi[5]

ABSTRACT: In this study a smart set-up integrated with rock bolts was proposed to automatically monitor, record and analyse rock mass deformation. The proposed system which includes sensors and a wireless data acquisition system, rapidly and readily generates data sets along with customisable graphs, calculations and analysis in a cloud system and can be used in modern mining. To evaluate the developed technique, rock bolts were instrumented lengthwise using resistive strain gauges and then connected to the wireless data logger system. Elastic tensile tests as well as pull-out tests were conducted and the strain values along the rock bolts were successfully and accurately measured, recorded and uploaded to the cloud system.

INTRODUCTION

The stability of underground excavations and surface slopes is a primary concern for engineers to improve workers safety, reduce environmental issues and avoid financial loss. Ground support is a general term describing the materials and methods used to improve the stability of rock mass. This term can be categorised differently depending on the conditions; for instance, if it applies an active load to the rocks (i.e., active or passive).

Rock bolts are widely used in mining and geotechnical engineering and are capable of effectively improving the stability of rock mass, reduce the rock mass deformation, resulting in improvement in safety, cost and time. Regardless of the type, rock bolt systems generally develop forces in response to rock deformation and displacement. Fully-grouted rock bolt installation is considered as the most common type of rock bolts in mining and civil engineering. Once a fully-grouted rock bolt is installed and rock mass starts to displace, the bolt interacts with the grouted materials and surrounded rock mass and load is transferred from unstable rocks to the intact rock. Rock bolts restrain rock movement along a discontinuity and control the rock deformation along the grouted length. When a fully-grouted bolt is subjected to a tensile force, a part of the axial stress is distributed at the bolt-grout interface, the grout, the grout-rock interface and the rock. The failure can occur in the bolt, at the bolt-grout interface, at the grout, at the grout-rock interface, inside the rock depending on the type, magnitude, and direction of stress besides the mechanical characteristics of the components. There are several robust software systems available in the market to design effective supporting systems to act as the shield for workers and equipment, nevertheless comprehensive and continuous monitoring programs are necessary to ensure the safety of the excavations. Monitoring is traditionally approached by surveying the opening periphery and/or measuring deformation of ground in the vicinity of the supporting elements e.g., multi-point rod extensometers. These approaches generally investigate the whole ground condition rather than a direct investigation of the interaction between the ground and the element itself. Furthermore, phenomenal deformation of rock mass occurs suddenly without precaution signs, and it may not be detected by ordinary approaches, while supporting elements experience high degree of tension.

Axial performance of rock bolts is usually investigated by capturing the load-displacement curves and/or induced strain of the bolt along the encapsulation length. This can be achieved using sensors such as Linear Variable Differential Transformers (LVDTs), load cells, vibrating-wire sensors and extensometers resistive strain gauges (SG), and fibre optic sensors (FOS).

---

[1] *Centre for Future Materials (CFM), University of Southern Queensland, email:* hadi.norizadeh@usq.edu.au,
[2] *School of Civil Engineering and Surveying, University of Southern Queensland, email:* ali.mirzaghorbanali@usq.edu.au
[3] *School of Civil, Mining and Environmental Engineering, University of Wollongong, email:* naj@uow.edu.au
[4] *School of Civil Engineering and Surveying, University of Southern Queensland, email:* kevin.mcdougall@usq.edu.au
[5] *School of Mining Engineering, Shahid Bahonar University of Kerman, email:* ak.sahebi@gmail.com

Singer (1990) used electric sensors to analyse the behaviour of rock bolts. He conducted field pull-out tests on the strain gauged rock bolts in varied geological conditions and concluded that the results compared well with the experimental studies and numerical models. Singer et al. (1997) conducted another study by which axial and shear behaviour of rock bolts were measured using strain gauges. The sensors were located along the length of fully grouted rock bolts installed in the roof of coal mines. Grasselli (2005) developed an experimental set up to investigate the response of the rock bolts in direct shear testing. Each steel rebar was equipped with five pairs of resistive strain gauges to directly measure the bolts deformation during experimental tests. Zhang et al. (2006) studied the load transfer mechanism of fibre-reinforced tendons by carrying out laboratory tests using resistive SG, embedded SG, FOS and LVDTs. Zhao et al. (2015) updated the control system of a servo testing machine and developed a jig to run pull-out tests on anchored rebars. To achieve the induced shear stress, two symmetric grooves were cut on the bolts and strain gauges were arranged in cuttings. Huang et al. (2013) manufactured a self-sensing fibre reinforced polymer anchor with a built-in optical fibre sensor. Forbes et al. (2018) presented a technique for measuring the induced strain distribution along supporting elements. There are usually two methods to couple deformation sensor with rock bolts: (i) surface coupling (ii) and subsurface or internal coupling. In surface coupling the sensor is mounted on the surface of the rock bolt, however grinding and polishing the surface might be necessary for better bonding. Opposite to the surface mounting, subsurface mounting can be approached by machining lengthwise grooves on the rebar and then the sensor is attached using a specific adhesion internally. Zhao et al. (2018) compared the effects of groove shape and glue materials for the bolt equipped with fibre optic sensors. Six different shapes including U-shape groove, U-shape groove with chamfer, inverted trapezoidal-shape groove, trapezoidal-shape groove and V-shape groove were analysed and it was concluded that the trapezoidal-shape groove has the best results. The surface coupling approach can effectively provide information about the deformation of the encapsulated rock bolts particularly in laboratory studies, however sensors get damaged at higher loads because of their direct exposure to the grouting materials (TeymenandKılıç 2018). Accordingly, the internal method for instrumentation of rock bolts was used in this study to capture and perform a full-scale deformation analysis along the rock bolts.

Conventionally reading and collecting the recorded data through all abovementioned equipment are limited to manual inspection. This can be time consuming and costly, and more importantly eliminating accurate and timely risk and safety assessment. Alternatively, popular wireless systems can be used to continuously monitor ground conditions. Within this context, this study proposes a smart set up to automatically monitor, record and analyse rock mass deformation. The proposed system which includes sensors and a wireless data acquisition system, rapidly and readily generates data sets along with the user-friendly graphs in a cloud system and consequently can be used in modern mining. Real time monitoring of ground conditions will lead to effective actions, avoiding the occurrence of potential life-threating hazards and consequently financial loss.

EXPERIMENTAL PROGRAM

Specimen preparation

Pull-out test, which is known as the common method in investigation of rock bolts behaviour, was performed in this research to explore the workability of the proposed method in practise (Nourizadeh et al., 2021). The tensile test was conducted on a double-sided strain gauged rock bolt using both a conventional data acquisition system and the new wireless set-up to check and compare the possible errors and create adjustments. While the pull-out tests were employed to remotely measure the full-scale induced deformation along the rock bolts encapsulated in concrete samples. The rock bolt used in the tests was a 24 mm diameter threaded rebar (*M24 X* Coal Bolt) manufactured by Minova Australia. For the surrounding rock, concrete with a UCS of approximately 40 MPa was cast in a steel pipe (CHS) with an inside diameter of 154 mm and thickness of 5.4 mm. The quality of the pipe was according to AS/NZS 1163 and AS 1074 standards. The confining materials (steel pipe and concrete) were selected and designed so that the confinement simulates a medium strength rock. Prior to casting the concrete, a 28 mm PVC tube was placed in the centre of the steel pipe as the bolt hole. A flexible polyvinyl tube with 4 mm in diameter was wound around the central PVC tube to create a rifled borehole and to mimic the in-situ conditions (**Figure 1**). In order to create a uniform interfacial shear stress throughout the encapsulation length, the rifling was designed such that the pitch was zero. To make sure the bolts are installed exactly in the centre of the concrete cylinders, one large hole of 161 mm diameter and a depth of 10 mm was machined on a 30 mm wooden plate to place and fix the steel cylinders. Also, two more holes were machined and drilled in the centre of the previously machined large hole with diameters of 28.1 and 24.1 mm for the PVC tube and the bolt, respectively (**Figure 2**). 150 mm of the rock bolt was instrumented and grouted inside the central hole using Type A Pour and Mix Resin (**Figure 3**).

Figure 1: Simulating the refiling in the specimen preparation

Figure 2: PVC tube used for rifling and hole for installing the bolt

Figure 3: concrete cylinder

Rock bolt instrumentation

The rock bolts used in this study were modified with a pair of opposed right angle U-shape grooves (4×4 mm) (**Figure 4**). These grooves were machined diametrically along the longitudinal ribs of the rock bolts. The monitoring of the axial deformation and stress was achieved by mounting the resistive strain gauges along the embedment length. The resistive strain gauges, 3 mm in length with a nominal Gauge Resistance of 120 Ω were bonded directly inside the grooves using Cyanoacrylate adhesive. Therefore, the induced strain in the rock bolts can be directly transferred to the coupled strain gauges and consequently can be transduced to electrical signals received in the data acquisition system. Four strain gauges were mounted every 50 mm on the bolts with 150 mm encapsulation lengths. It should be noted that the strain gauges were bonded one in between on the opposed grooves because of space constraints in passing the lead wires. Furthermore, in order to protect the strain gauges and lead wires, an organic and nonacidic sealant was applied to fully cover the instruments and the grooves (**Figure 5**).

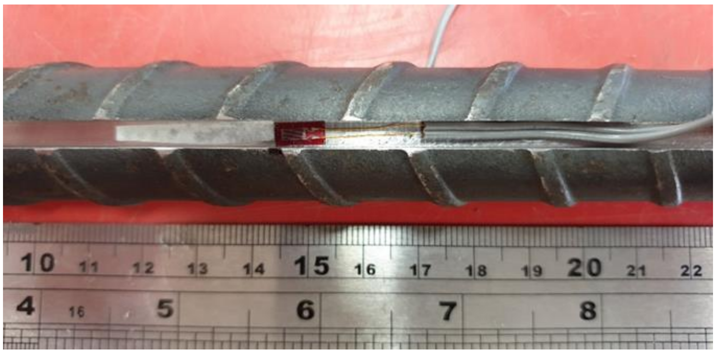

Figure 4: Bonding strain gauges inside the grooves

Figure 5: Instrumented and sealed rock bolts

Testing equipment

The value of strain caused by the pull-out force is calculated by measuring the change in the gauge resistance which is a result of the elongation of the bolt due to the applied axial load. The resistance change is much smaller compared to the strain gauge resistance itself, thus it is required to be measured accurately. Usually, a Wheatstone Bridge Circuit is used to measure this small resistance change. There are different types of Wheatstone Bridge Circuits such as Quarter, Half and Full Wheatstone Bridges which should be used depending on the measurement task. In this study, the Quarter type was designed and used (**Figure 6**).

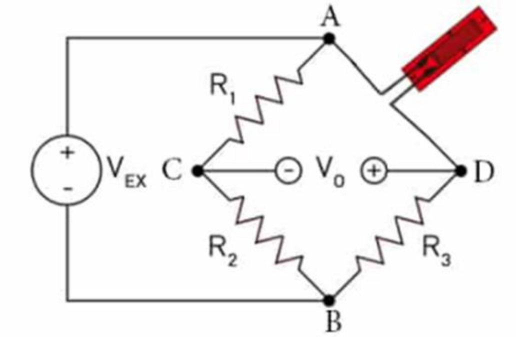

Figure 6: Wheatstone Bridge Circuit

Here;

$$V_0 = \frac{V_{ex}}{4} \times k \times \epsilon$$

where V_0 is voltage change, V_{ex} is excitation voltage, k is gauge factor and ε is the induced strain. When the distance between strain gauge and the other three resistors is not equal, e.g., longer lead wire, the output voltage can be impacted. In this case the undesired effect can be rectified by connecting a third wire to the upper wire of the connected strain gauge.

To supply the power (V_{ex}) in the circuit and also to measure and record the output voltage (V_0) created in the resistance bridge, a millivolt sensor node was used and connected to the manufactured Wheatstone Bridge. Basically, this unit works as a convertor to translate the change in the strain gauge resistance to the voltage change. The millivolt sensor node uses an integrated mesh radio transceiver with the frequency of 2400-2485 MHz to report the measurement through the wireless communications network. Also, a built-in is a 19000 mAh Lithium Thionyl Chloride battery which provides the input voltage of the system. The device can communicate remotely with the receiver to a maximum range of 300 m depending on the environment and fitted antenna with maximum transmit power of 6.5 dBm and maximum antenna gain of 2.2 dBi. The bridge circuit was connected to the sensor node using an M12 female connector providing a range of ±0.625 V and a stimulus of 5.0±0.1 V. The strain data converted in the millivolt sensor node is sent directly and remotely to a receiver which is called a 4G Gateway system, afterwards. The 4G Gateway system is a fully integrated unit which provides all the functionality required to operate a wireless sensor network in a remote location. The Gateway with built-in cellular service simply initiates the connection with the WebMonitor software over the internet to upload the data in the cloud system. The Gateway system can be integrated with a solar circuit for charging the internal lithium-ion chargeable battery. The system can fully operate for three weeks on the internal battery without recharging. The Web-Monitor is a web-based data access system run on a Microsoft Azure cloud platform and provides a tool for the management of monitoring solutions deployed in the field. The data can be transferred to other systems with different options including FTP(S) uploads in a variety of formats and an HTTP API. **Figure 7** shows the wireless unit.

Pull-out and tensile tests were carried out using a servo-controlled 1000 KN Instron testing machine. Furthermore, a frame was designed and manufactured at the Engineering Workshop the University of Southern Queensland using high tensile materials to place and fix the specimen in the pull-out process (**Figure 8**).

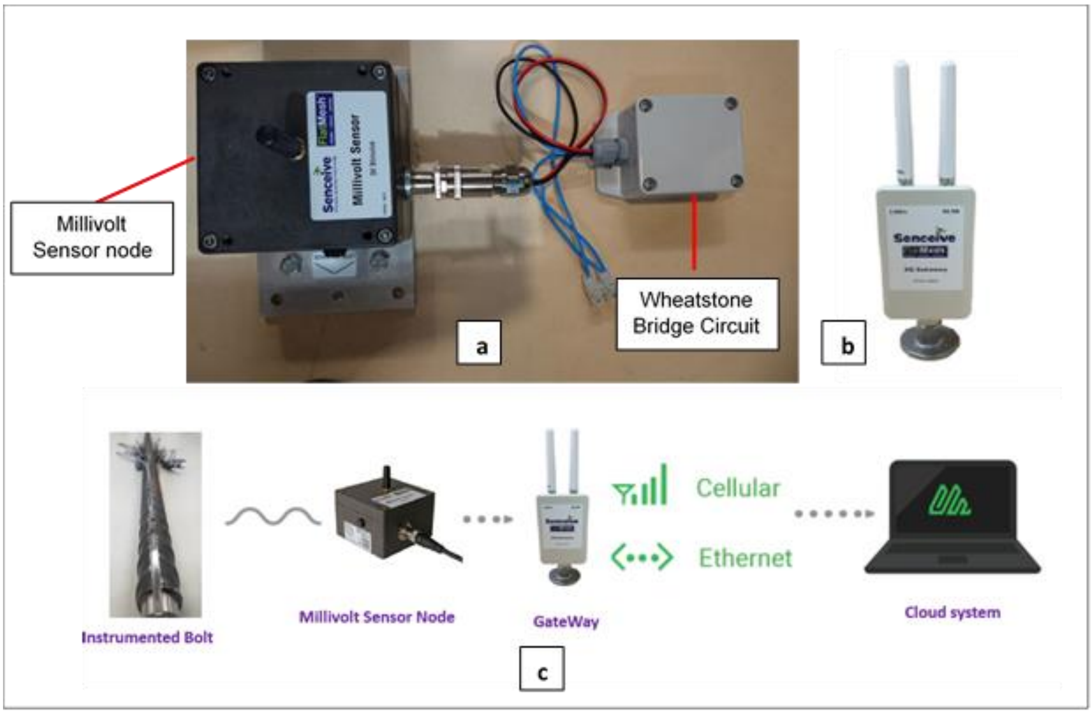

Figure 7: (a) Millivolt Sensor Node connected to the Wheatstone circuit, (b) the wireless Gatewway, and (c) the schematic of the whole measuring system

Figure 8: Pull-out test set-up

TEST RESULTS

Validation of the accuracy of the developed wireless set-up was accomplished by performing a tensile test with a 600 mm testing span using the 1000 kN servo-controlled machine. Similar to the procedure followed in preparing the specimens for the pull-out tests, two 170 mm lengthwise grooves were machined symmetrically on a 600 mm rebar. Two strain gauges (with same characterisations and equal wires length) were bonded carefully on the grooves such that the backing ends of the gauges are aligned crosswise. Thereafter, the instrumented bolt was clamped into the machine's jaws from the top and bottom. One gauge was connected to an analogue DT800 data collection system, while the other was attached to the Millivolt Sensor Node for remote monitoring (**Figure 9**). After completion of the wire connections, the signals received from the gauges were reset in the software systems. The load was applied cyclically up to a maximum value with different rates and simultaneously the load-displacement was measured by the load cells and LVDTs and recorded in the software. While the strain data was monitored and recorded by both wired and wireless systems over the same interval frequency. It is noted that the tensile load was subjected to the bolt in a way that the induced tensile stresses always remained in the elastic zone. A comparison of the strains recorded by the systems over time is presented **Figure 10**. As can be seen in the figure, there is a good correlation between the results obtained from DT800 data logger system and the wireless system demonstrating that the wireless data collection system is capable of measuring strain values accurately. The negligible differences between the recorded results are attributed to the accidental error during strain gauges installation.

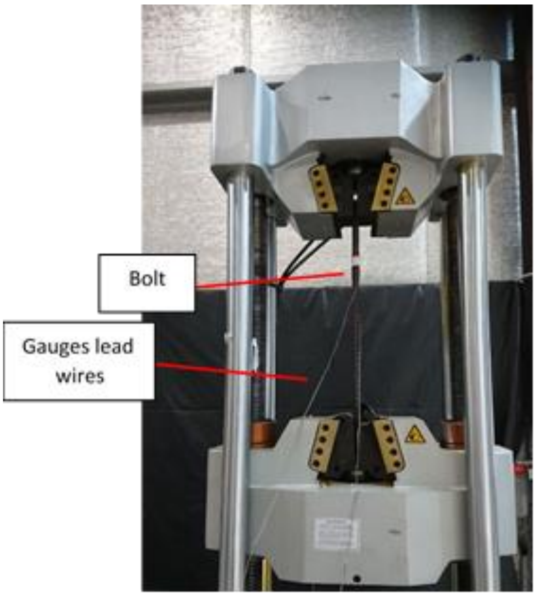

Figure 9: Conducted elastic tensile test

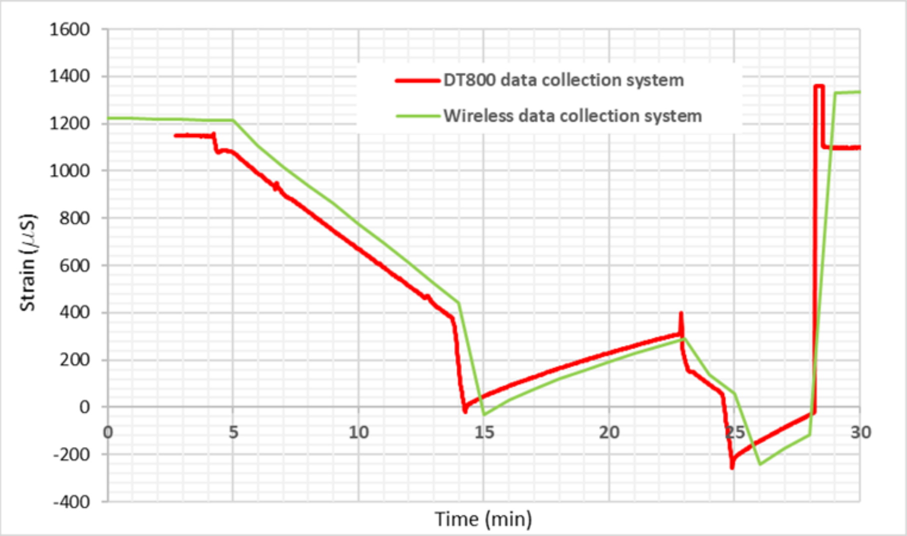

Figure 10: Comparison the strains obtained from the DT800 analogue system and the wireless system

The rock bolt embedded in concrete cylinders was subjected to pull-out load and the values of load, deformation and strains were measured immediately. Strain values were collected using the wireless data collection system and stored in the cloud system; however, the load-displacement was recorder by the servo-controlled machine (**Figure 11**). **Figure 12** shows the strain data collected by the wireless system. Sensor 1 is the closest sensor to the loading point, while sensors 2, 3 and 4 are located further away from the loading point. It is inferred from **Figure 12** that at a certain level of pull-out load (or at a certain time) the strain values decrease as the sensor distance increases from the loading point. In addition, the strain values follow a similar trend as the load-displacement curve (**Figure 13**), indicating that the strain gauges arrangement successfully measure the deformations. In addition, it can be concluded that the failure of the rock bolt occurs when the stain-time curve bends over. **Figure 14** also illustrates the specimen after pull-out testing and shows that a full-scale pull-out test was conducted successfully.

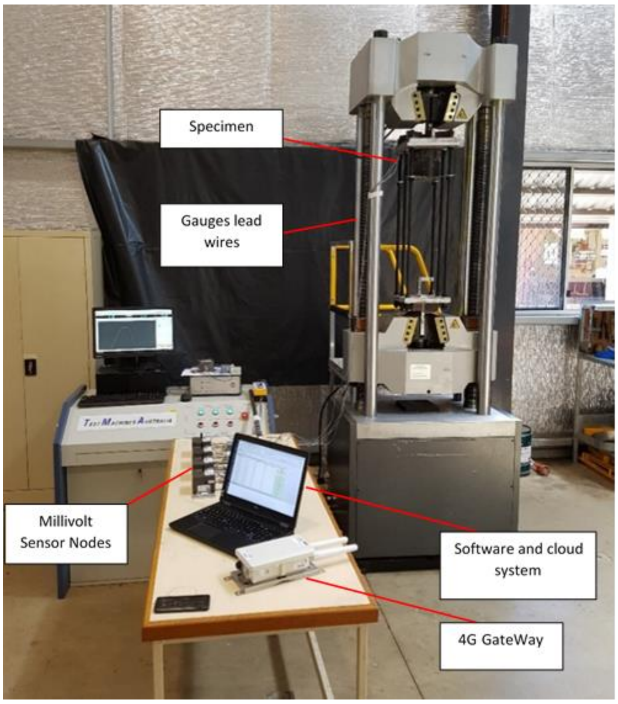

Figure 11: Pull-out testing and wireless monitoring system

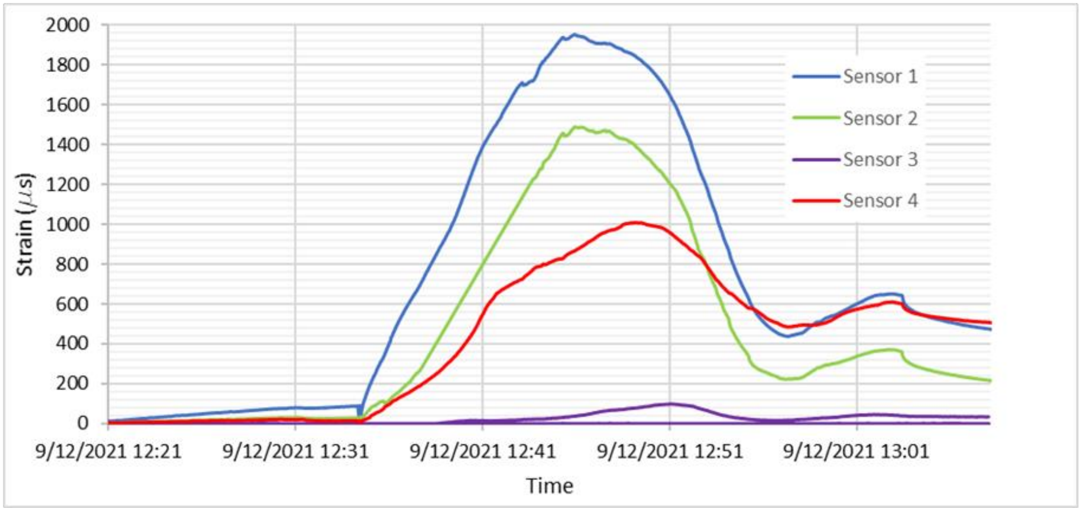

Figure 12: The strain recorded by the wireless collection system over time

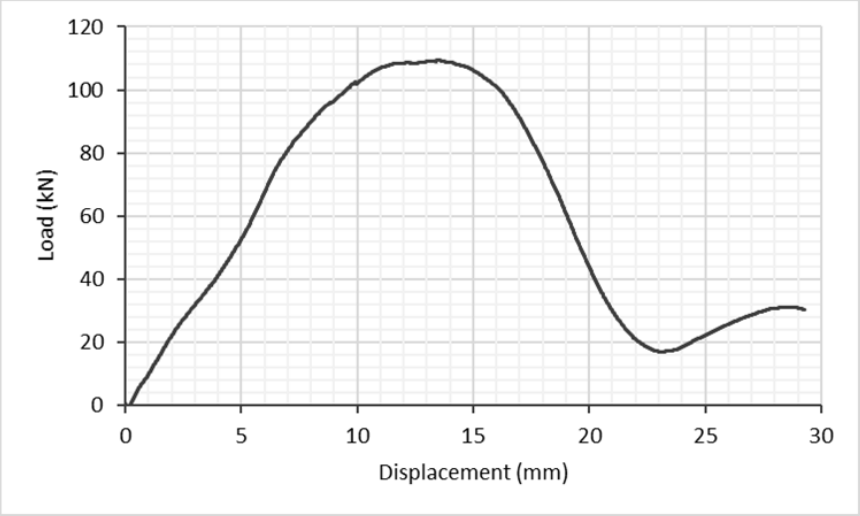

Figure 13: The load-displacement curve obtained from the pull-out test

Figure 14: The specimen after completion of pull-out test

CONCLUSIONS

This study proposes a smart set-up to automatically monitor, record and analyse rock bolts performance and behaviour. The proposed system which is comprised of sensors and a wireless data collecting system, rapidly and readily generates data sets along with the user friendly graphs in a cloud system. A single tensile test was conducted to evaluate the accuracy of the wireless data logger system and it was observed that there is good agreement between the results obtain from the analogue and the wireless systems. Then, an instrumented rock bolt with the encapsulation of 150 mm was grouted in a concrete cylinder and subjected to pull-out load. Simultaneously the strain and deformation of the rock bolts was measured and recorded by the wireless set-up. The results showed that the proposed technique is capable to record the data with high accuracy. However, it is recommended to carry out more tests such as in-situ pull-out tests as well as laboratory tests with longer embedment lengths.

ACKNOWLEDGMENTS

Authors would like to cordially acknowledge Jennmar Australia, Minova Australia, Position Partners, and Senceive’s *in-kind* supports in various stages of this research study. Grateful thanks also shall be extended to Dr Peter Craig, Mr Robert Hawker, Mr Thomas Drewett and Mr Heath Low for their valuable advice and supports.

REFERENCE

Forbes, B, Vlachopoulos, N, Hyett, A, 2018. The application of distributed optical strain sensing to measure the strain distribution of ground support members. Facets, vol. 3, no. 1, pp. 195-226 DOI: 10.1139/facets-2017-0093.

Grasselli, G, 2005. 3D Behaviour of bolted rock joints: experimental and numerical study. International Journal of Rock Mechanics and Mining Sciences, vol. 42, no. 1, pp. 13-24 DOI: 10.1016/j.ijrmms.2004.06.003.

Huang, M, Zhou, Z, Huang, Y, Ou, J, 2013. A distributed self-sensing FRP anchor rod with built-in optical fiber sensor. Measurement, vol. 46, no. 4, pp. 1363-70 DOI: 10.1016/j.measurement.2012.12.012.

Nourizadeh, H, Williams, S, Mirzaghorbanali, A, McDougall, K, Aziz, N, Serati, M, 2021. Axial behaviour of rock bolts-part (A) Experimental study, Proceedings of the 2021 Resource Operators Conference Resource Operator, University of Wollongong, Wollongong, NSW, Australia.

Singer, S.P, 1990. Field verification of load transfer mechanics of fully grouted roof bolts. United States Departement of the Interior (Bureau of Mines), USA, 9301.

Singer, S.P, Cox, D, Johnston, J, 1997. A method for the selection of rock support based on bolt loading measurements. Spokane Research Center (NIOSH), USA.

Teymen, A, Kılıç, A, 2018. Effect of grout strength on the stress distribution (tensile) of fully-grouted rockbolts. Tunnelling and Underground Space Technology, vol. 77, pp. 280-7 DOI: 10.1016/j.tust.2018.04.022.

Zhang, N, Benmorkane, B, Ebead, U.A.A, 2006. Design and Evaluation of Fiber-Reinforced Polymer Bond-Type Anchorages and Ground Anchors. International Journal of Geomechanic, vol. 166 DOI: 10.1061/(ASCE)1532-3641(2006)6:3(166).

Zhao, T.B, Guo, W.Y, Yin, Y.C, Tan Y.

L, 2015. Bolt Pull-Out Tests of Anchorage Body under Different Loading Rates. Shock and Vibration, vol. 2015, pp. 1-8 DOI: 10.1155/2015/121673.

Zhao, Y, Zhang, N, Si, G, Li, X, 2018. Study on the Optimal Groove Shape and Glue Material for Fiber Bragg Grating Measuring Bolts. Sensors (Basel), vol. 18, no. 6, DOI: 10.3390/s18061799.