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Monitoring of rock stress change using instrumented rebar rock bolts

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Abstract. Rock stress is causing unwanted deformations of deep underground spaces. Large deformations increase the risk of failure. The underground excavation causes rock stress changes in the surrounding rock mass, and the resulting deformations can be measured. In this paper, we present a method to monitor stress changes in the rock mass using rebar rock bolts instrumented with strain gauges to track the stress within the bolt. Next to that, we describe in-situ testing of this method using heating-induced stress in a natural underground environment. The heating experiment aims to create stress changes using rope heaters inserted into the rock mass and located symmetrically around a single instrumented rock bolt. The heat flux induced to the rock mass leads to volume expansion. The restricted thermal expansion causes an increase in the internal rock stress conditions. These conditions create a strain that can be measured and backcalculated as the rock stress change. The instrumented rock bolt and testing setup were installed in the Underground Research Laboratory located in a granitic rock below the Aalto University campus. The single bolt experiment demonstrates how instrumented rock bolts could monitor the changes in the rock mass stress state. The system can be used as a part of a real-time rock stress monitoring system in mining and rock engineering projects. The final part of the paper describes how this monitoring system can positively affect geotechnical risk management and increase the overall safety of underground construction.

1. Introduction

Some of the collapses of underground spaces are caused by a sudden increase of stresses in the surrounding rock mass. The origin of the rock stress change can be due to tectonics as well as man-made excavation processes and stoping. High magnitudes of rock stress result in large deformation of underground spaces leading to collapse such as rock burst. Therefore, a better prediction and understanding of rock behaviour to prevent failures and ensure safe work conditions is crucial in the risk management of underground structures [1].

Throughout the years, several investigation methods were developed to measure changes in rock stress using various tools and procedures. One of the main rock stress measurement methods is the overcoring method, well-known for its precise results and direct application at the location of interest. However, the overcoring method measures the rock stress only at one time, and for continuous monitoring, it is necessary to perform this method multiple times in a sequence. The improvement to ensure rock stress monitoring method over time came from Norwegian laboratory SINTEF which has developed so-called long-term door stoppers [2][3]. This method uses a long-term door stopper cell equipped with a strain gauge rosette attached to the bottom of a borehole in the rock mass. However, the real rock stress is only measured at the location close to the door stoppers at the point of interest.

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The paper aims to demonstrate the use of instrumented rebar rock bolts as a solution to rock stress monitoring and present the benefits of this new monitoring method to risk and safety assessment in underground structures. This paper is based on a Master's thesis completed as part of the REMOS (Real-time monitoring of rock stress) project at Aalto University in Finland [4]. REMOS aims to develop a solution of rock stress monitoring calculated from data based on the strain measurements and support of numerical modelling [5][6][7].

Rock bolt is a protective reinforcement element used in underground mines, tunnels, and open rock slopes [8]. The main idea of using instrumented rock bolts is to combine rock mass reinforcement with measurement and data analysis. The rock bolts can be installed using conventional methods of rock bolting and, in addition, can be applied for monitoring the behaviour of the rock mass. Instrumented rock bolts can also be used for rock stress monitoring as long as the rock mass immediately around the tunnel is behaving elastically. Support of IoT devices can transform instrumented rock bolts into so-called smart rock bolts with innovative monitoring of rock mass data in real-time and presenting results on computers, tablets, or smartphones. The smart rock bolt consists of strain gauges, a data analyzer, and a built-in computer.

2. Methodology

To demonstrate the use of instrumented rock bolt as a rock stress monitoring tool, an experiment in the Underground Research Laboratory of Aalto University (URLA) was conducted. The URLA is located approximately 20 m below ground in granitic rock. The shallow depth of the URLA does not provide a high-stress environment. The initial idea of the experiment was to cause an elastic deformation in the rock mass and induce measurable changes in rock stress using an artificial method [4].

Thermal stress was selected as the most suitable method of causing a measurable rise in the rock stress using a rock as a material with thermal conductivity properties. The rock mass in the URLA is moderately fractured and consists of several fracture zones, which can highly affect the heat distribution as well as the rock stress state in the rock mass. Therefore, from the geological point of view, a suitable location for the field experiment was selected so that the rock mass is, to a sufficient extent, continuously homogeneous around the rock bolt.

2.1. Numerical-model-based design of the experiment

The design process of the experiment setup was aiming to develop heat in the rock mass with values high enough to measure the elastic deformation. The deformation of the rock mass was restricted in the vertical direction and along the tunnel axis by the rock mass. This causes a rise of stresses measurable by sensors of the instrumented rock bolt.

The number, position, and orientation of heat sources were designed in a 3D numerical model with time steps made in FEM software COMSOL® Multiphysics 5.5. The final design (figure 1), resulted in the implementation of 8 linear heaters with a power of 167 W/m and a length of 3 m. Heaters were located in parallel boreholes symmetrically drilled around an instrumented rebar rock bolt with a length of 3 m. The radial distance between the heaters and the rock bolt was designed as 0.5 m. The heat flux and temperature rise in the rock mass were numerically modelled considering rock material properties obtained from laboratory tests in the underground laboratory, as shown in table 1 [4].

The final temperature of the rock mass around the middle length of the instrumented rock bolt was predicted to be 45 °C after 50 hours of heating. The heat distribution within the rock mass was modelled as shown in figure 1. The temperature reached measurable magnitudes of strain already after 50 hours of heating. Hence, the experiment was designed for 100 hours from which the first 50 hours consist of constant heating and the next 50 hours consider only monitoring without heating. With these settings, it was possible to measure the increase and decrease of strain along the instrumented rock within the range of only 100 hours.

1 1	C		e
Property	Value	Unit	Source
Young's modulus	75.3ª	GPa	Lab test [4]
Poisson's ratio	0.24 ^b	-	Lab test [4]
UCS	265.3	MPa	Lab test [4]
Density	2640	kg/m ³	Lab test [4]
Heat capacity	723.5	J/(kg·K)	Lab test [9]
Coefficient of thermal expansion	7.10^{-6}	1/K	Assumed based on literature
Thermal conductivity	2.97	W/(m·K)	Lab test [9]

Table 1. Rock properties of granite from URLA site used in numerical modelling.

^a In thermal modelling value of 60 GPa was used ^b In thermal modelling value of 0.25 was used



Figure 1. Numerical prediction by COMSOL of the heating test – cross (left) and longitudinal (right) section [4].



Figure 2. Instrumented rock bolt with the measured distances between heaters and locations of temperature sensors [4].

2.2. In-situ experiment

The test tunnel of URLA provided the required spaces, equipment, and professional supervision to perform all experiments and tests related to the REMOS project. The rock wall for the experiment was selected based on rock mass homogeneity, number and direction of fractures, and the size constraints of the drill rig. To induce the increase of rock stress, linear rope heaters were inserted into the rock mass and connected to electricity. The directions of boreholes, as well as distances between boreholes, were measured by a hand-held laser distance meter after the drilling process and installation of the instrumented rock bolt. The measured distances of heating holes around the instrumented rock bolt are

shown in figure 2. Linear rope heaters were inserted into an aluminium pipe to ensure easy installation and higher heat transfer from the source to the rock mass.

The temperature development was monitored before, during, and after the experiment using independent temperature sensors at three locations on the test setup (figure 2). The temperature sensor no. 5 was placed on the rock wall surface near the washer head of the rock bolt and the temperature sensors no. 4 and no. 6 were placed in empty holes located between two heating holes in the depth of 0.7 m (sensor no. 4) and 1.0 m (sensor no. 6). Also, one extra sensor was attached to the surface of the instrumented rock bolt in the middle of its length.

Monitoring of the data was done with a frequency of 0.043Hz (2.6 measurements per minute) using a data logger compiled of IoT components, amplifiers, and electrical circuit. Wheatstone quarter-bridges were used to read changes in the voltage in one-dimensional strain gauges attached to the rock bolt.

2.3. Strain monitoring

The rise of temperature in the rock mass caused deformation and increase of the rock stress measurable via axial strain of the rock bolt. One-dimensional strain sensors were attached at designed locations onto the surface of the rock bolt (see figure 3) to monitor the axial strain by tracking raw signals in bit units corresponding to the voltage change in the electric circuit of the quarter bridge. These raw signals tracked by amplifiers in the data logger were automatically recalculated to voltage change. Voltage magnitudes were then manually recalculated to strain using formulas for Wheatstone quarter-bridge with 3-wire configuration. The effect of temperature on the sensors was calculated separately and deducted from the measured strain magnitudes. Final strain progress over the time during the experiment was analyzed and cleaned from noise data and used to calculate rock stress change. In addition, the initial value was estimated as a start of the strain development and a zero point of the rock stress change.

2.4. Strain to rock stress back-calculation

The idea behind the rock stress back-calculation method is based on Hooke's law referring to the relationship of stress and strain in the material of certain Young's modulus. The back-calculation method was implemented into a REMOS code developed during the REMOS project. The code was built on a rock stress estimation algorithm using multiple linear regression converting real strain data into stress changes with numerical modelling. The advantage of the code is its possibility of implementation into IoT devices and obtaining results in real time simultaneously with the monitoring process.

Strain values obtained during the heating experiment were imported to the REMOS code used to back-calculate rock stress from strain. The main goal of the heating experiment was to evaluate if the recorded strain data reflect the stress change in the rock mass. It is important to point out that the heating experiment was used only to cause strain measurable and recordable by sensors of the instrumented rock bolt. Hence, this paper does not focus on the real rock stress equivalent to the heat development in the rock mass.

The back-calculation process was supported by numerical modelling. A 2D numerical model (see figure 4) considering the theoretical shape of the tunnel profile, positions of sensors on the instrumented rock bolt in the rock mass, and relevant rock material parameters, was created in Rocscience Examine 2D 8.0 BEM software. This 2D numerical model was different from the model used for simulating heat flux effect in the rock mass and design of the experiment setup. The results in the form of unit responses served as a source of data required for the multiple linear regression implemented in the REMOS code. The load was applied as external in the 2D numerical model causing a concentration of stresses by the tunnel profile. However, the thermal expansion in the experiment occurs close to the rock bolt without considering the tunnel profile and its stress concentration. Hence, a correction factor of 1.45 was calculated due to the difference of load applications and applied to the results from the numerical model to remove stress concentration effect of the tunnel excavation.

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Figure 3. Schema of instrumented rock bolt with data logger [4].



Figure 4. The geometry of a test tunnel used for Examine 2D numerical model, the distribution of unit horizontal rock stress, and the horizontal stress responses σ_{XX} for each sensor in MPa [4].

	Synthetic data - input		Results -	output
	Horizontal stress [MPa]	Vertical stress [MPa]	Horizontal stress [MPa]	Vertical stress [MPa]
Test no.1	100	0	100.000	0.000
Test no.2	0	50	0.281	49.574
Test no.3	75	30	74.653	30.524

Table 2. Results from the synthetic test of rock stress calculation.

The algorithm uses strain responses from the 2D numerical model calculated as reactions on unit stress states. The unit stress states were defined as the stress of 1 MPa in horizontal, vertical, and shear directions. The stress in the direction of the smart rock bolt was calculated at each location of the strain sensor using formula (1) to calculate relevant strain response. Unitless strain response was calculated as the stress response divided by Young's modulus. Before importing data obtained from the heating experiment, several tests using synthetic data with pre-defined values were performed to confirm the correctness of the back-calculation by comparing input and output values. Results from synthetic tests are shown in table 2.

$$\sigma'_{i} = \sigma_{XX,i} \cos^{2} \theta + \sigma_{YY,i} \sin^{2} \theta + 2\tau_{XY,i} \sin \theta \cos \theta \tag{1}$$

Where σ' = stress response in the direction of the smart rock bolt, σ_{XX} = stress response in a horizontal direction, σ_{YY} = stress response in a vertical direction, τ_{XY} = shear stress response, θ = inclination angle (5°), *i* = number of strain sensor (1, 2, 3)

3. Results

The data from the field experiment were analyzed and used for back-calculation using the REMOS code. Results of strain corresponded to the development of heat in the rock mass based on the heating cycle. Strain monitored along the instrumented rock bolt showed a clear rise of magnitudes which can be interpreted as a rise of internal stress conditions. The progress of the strain at three locations along the instrumented rock bolt is shown in figure 5. Measurements from three independent temperature sensors located on the rock wall surface are presented in figure 6.



Figure 7. Result of horizontal and vertical rock stress change.

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3.1. Rock stress change results

Strain values were imported to REMOS code together with the unit responses from the 2D numerical model based on the tunnel geometry and position of the instrumented rock bolt. The code using the rock stress estimation algorithm estimated differences in horizontal and vertical rock stress from their initial values, as shown in figure 7. The dotted lines show the theoretical thermal stress using the measured heat from temperature sensor no.6. The predicted theoretical thermal stress curves were calculated using formula (2).

$$\sigma_{x \ thermal} = -2\nu E\alpha\Delta T \ ; \ \sigma_{v \ thermal} = E\alpha\Delta T - \nu E\alpha\Delta T \tag{2}$$

Where $\sigma_{x_thermal}$ = predicted thermal stress in a horizontal direction, $\sigma_{y_thermal}$ = predicted thermal stress a vertical direction, v = Poisson's ratio, E = Young's modulus, α = coefficient of thermal expansion, ΔT = measured temperature change in the rock mass during the heating experiment.

4. Discussion

The introduction of heat into the rock created additional stress in the rock mass measurable using a simple instrumented rock bolt. However, the exact rock stress change was not possible to calculate due to thermal distortions during the heating experiment. Strain recorded by instrumented rock bolt was used only as a simulation of a pure mechanical strain, normally representing a real underground case. Also, only horizontal and vertical stress changes were estimated without predicting changes in shear stress. Significant magnitudes of shear stress were not expected based on the numerical modelling.

4.1. Outcomes from the experiment

The experiment determined the usability of instrumented rock bolt not only as a regular part of rock mass reinforcement but also as a rock stress monitoring instrument. The solution combining these two roles is unique in underground projects, and it can lead to a rise in demand for this monitoring method resulting in effective cost-savings. Next to that, the advantage of the REMOS code is that it can automatically calculate changes in rock stress in real time. Besides, implementing IoT devices brings an opportunity to monitor the rock mass behaviour online using an app connected to the cloud database.

4.2. Effect on the geotechnical risk management

Real-time rock stress change measurements using instrumented rebar rock bolts may help to monitor the rock mass response around the excavations caused by mining activity. Online access to in-situ stress information can then optimize the sequence of excavation to decrease unplanned ore dilution and ore losses, which would have a positive effect on production. Also, a better knowledge of the actual stress change can help identify and quantify the level of geotechnical hazards related to high stresses so that more optimal ground control procedures can be put in place [10]. Real-time rock stress change measurement can be subsequently used to do real-time risk monitoring of stress-induced failures.

One such approach is through the use of Bayesian networks (BN) to continuously update the likelihood of a failure using feedback from the REMOS code. When the hardware is first deployed in a mine, initial thresholds can be set for various levels of stress change which define low, medium, and high risk. These thresholds can either be from historical data or expert opinion in the absence of historical data. The risk of stress-induced failures need not be qualitative and can be defined as the percentage likelihood of a failure based on the stress state change as shown in table 3. Through the process of backward inference, the actual probabilities in table 3 can be revised following every incident of rockburst. The model can be similarly expanded to model the consequence of each incident ranging from production stoppage to bodily harm and property damage.

As a result, an online risk management methodology can be implemented, which will ultimately lead to a safer work environment [11]. In practice, it means that every person involved in the exact excavation or mining project with access to the online monitoring service can be notified about the actual change in the state of the rock mass and can immediately react to the potential collapse.

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using real-time stress state change data.		
Real-time stress change (MPa)	Probability of rock burst	
1 to 5	10 %	
6 to 10	60 %	
> 10	85 %	

Table 3. Example of initial quantitative input to rock burst likelihood using real-time stress state change data.

5. Conclusion

The instrumented rock bolt equipped with the IoT data logger was able to record stress changes successfully. The recorded data were used as an example case of using the REMOS code to estimate rock stress changes in horizontal and vertical directions. The in-situ experiment demonstrated that heating is a convenient way to cause measurable stresses in the rock mass. The result from the REMOS code is similar to the theoretical values. The use of instrumented rock bolts is a viable option to monitor stress changes in rock spaces.

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