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Real time stress change estimation using strain measurements

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ABSTRACT: Mining and rock engineering projects often rely on limited stress measurement data. Aalto University developed a novel method with real time access to *in situ* stress state to optimize mining sequence, to reduce ore dilution, to improve working safety and to limit ore losses. The method is based on real time inversion calculation of the strain data, which is obtained using intelligent bolts or extensometers. Inverse calculation of the stress change is carried out using unit stress responses and superposition. The continuous, homogenous, isotropic, linearly elastic rock conditions are assumed for the rock mass and numerical modelling tools are used to generate the stress responses. Blind test challenges for the method were carried out to predict the robustness of the method in mine-like conditions. In synthetic tests the method performed well with good precision. Boliden's Kilylahti mine has been instrumented and the analysis of the data is being carried out.

1 INTRODUCTION

Mining and rock engineering projects often rely on limited stress measurements carried out at certain stages of the project. In number of cases previously, the stress state has been monitored during the excavation, however with significant amount of effort and using expensive stress measurement cells (Kaiser et al. 2001). However, strain measurements are a cheap and widely used method in the mining industry to monitor the rock mass response to mining (Shen et al. 2008 and Bergström et al. 2014). A method for estimating the *in situ* stress change around an excavation in elastic rock was developed and is presented in this paper. The estimation is based on real time strain data, obtained using extensometers or intelligent bolts.

Online and real time access to *in situ* stress state can be used to optimize the mining sequence, to reduce ore dilution and to limit ore losses. It can also support more precise reinforcement design and give the ability to detect and to react to unexpected changes while maintaining a higher level of safety and avoiding collapses. Stress state change monitoring is able to give feedback about the success of mining sequencing and sufficiency of ground control methods. With the real-time monitoring of the stress state, it is possible to increase the safety of underground mines especially if the stress changes cause significant risks.

The current state of the stress monitoring is concentrated to collect data for the mining sequencing and for the original designs. The objective of this research is to create a tool for the mines to monitor the stress state changes caused by the mining activities. By monitoring the actual change the design and the sequencing can turn into an iterative process.

2 INVERSE CALCULATION METHOD

The stress state change is back-calculated using linear regression of strain change observations, the elastic constitutive relation and the superposition principle. The algorithm used assumes continuous, homogeneous, isotropic and linearly elastic rock (CHILE) conditions.

2.1 Strain calculation using superposition

In CHILE rock mass, superposition of unit strains can be used to represent the strain state. With use of superposition of the strain state loading, total strain of selected sections within the medium may be calculated by simple summing up the components ($\Delta\varepsilon_{\sigma z}$, $\Delta\varepsilon_{\sigma x}$, $\Delta\varepsilon_{\sigma zx}$). In plane stress the total strain ($\Delta\varepsilon_{tot}$) may be calculated. For each of these components the strain may be expressed as strain from unit stress ($\Delta\varepsilon_{\sigma z1}$, $\Delta\varepsilon_{\sigma x1}$, $\Delta\varepsilon_{\sigma zx1}$) multiplied by a factor (L_z , L_x , L_{zx}):

$$\Delta\varepsilon_{tot} = L_z\Delta\varepsilon_{\sigma z1} + L_x\Delta\varepsilon_{\sigma x1} + L_{zx}\Delta\varepsilon_{\sigma zx1} \quad (1)$$

Any strain state can be represented using the constant unit strains and a set of factors corresponding to that strain. This strain state can then be converted into a corresponding stress state using the elastic modulus and the Poisson's value. It is important to note that both the strain and the stress are changes denoted with the delta. Solving the *in situ* stress would require a change between the *in situ* strain and the current strain.

2.2 Inverse stress calculation

The loading factors can be calculated using strain measurement data (e.g. extensometers) from excavation surroundings and numerical modelling of the excavation geometries with unit loads, leading to the change of the stress tensor around the excavation. At least three independent measurements are needed to be able to solve the loading factors for a two dimensional case or six for a three-dimensional case. When the amount of measurement exceeds this value, the set of equations becomes overdetermined and may be written as a vector form for later regression analysis.

In synthetic homogenous, elastic cases it is possible to perform the measurements exactly with only one solution existing even with overdetermined systems. For actual cases, this is not possible and an approximate solution must be found. If each combination of three lines of the whole set of equations are taken, it would be possible to find the loading factor vector for each of these combinations. When results are plotted as points in space of L_z L_x and L_{zx} a most likely solution could be found with the use of multiple liner regression.

2.2.1 Multiple linear regression

Multiple linear regression is a statistical method of modelling the relationship between a scalar dependent variables (y_i) and explanatory variables for parameters (β_i), input variables ($x_{i,1}$) and errors (ε_i). This method is suitable for stress-strain problems. The dependent variable is the measured strain in bolt section and the explanatory variables or parameters are the stress tensor components or loading factors as defined before. The multiple linear regression model is:

$$y_i = \beta_1x_{1,1} + \dots + \beta_nx_{n,1} + \varepsilon_i = x_iT\beta + \varepsilon_i, \quad i = 1,2 \dots n \quad (2)$$

In matrix form Y is the vector of dependent variables, X is the vector of input variables and β is the parameter vector and ε is the error vector. The equation becomes:

$$Y = X\beta + \varepsilon \quad (3)$$

2.2.2 Least squares estimation

Several estimation methods have been developed in the linear regression, of which the Least squares method is the most used estimator. The advantage is that it is an efficient and simple method. The method minimizes the sum of squared residuals and leads to closed-form expression for the estimated value of unknown parameters. The parameter vector is:

$$\beta = (X^T X)^{-1} X^T Y \quad (4)$$

The error is calculated as a difference between measured values Y and the values of the best fit as:

$$\varepsilon = Y - \beta X \quad (5)$$

When we obtain the error vector it may be good to compare the results and make a simple data analysis to find outliers and other wrong data which may influence the results.

3 BENCHMARKING

To validate the developed method for stress change back-calculation and the calculating algorithm, four major tests were carried out. Synthetic data was used in the method testing. Several 2D and 3D test case sets were analyzed. The first 2D blind test is described below in more detail.

3.1 2D blind test cases

Twelve synthetic blind cases were created (Table 1). There were cases with clear data, noisy data, clear data with missing data and few special cases, which are explained in detail. To simulate the real data structure five interval values were given for each instrument. The six points of the 10 m long instruments were located at depths of 4.4 m, 4.8 m, 5.2 m, 5.8 m, 7.2 m and 10 m. This pattern was chosen to weight the larger strains taking place closer to the excavation boundary.

Table 1. Description of 12 blind case test and achieved estimation results.

Case	Description	Estimation result
1-3	different stress state clear data	1: ~100 %, 2: ~100 %, 3: 99.7 %
4-6	noise 1 %, 5 % and 10 %	4: 98.4 %, 5: 92.4 %, 6: 96.0 %
7	clear data, three data points missing	~100 %
8	clear data, six data points missing	~100 %
9	clear data, one instrument missing (five data points)	99.9 %
10	unknown joint crossing all instruments	24.2 %
11	parallel joint set, not intersecting instruments	74.1 %
12	two instruments swapped	0 %

Data was obtained with boundary element numerical modelling software Examine2D 8.0. Geometry of the excavation and elastic rock properties were the same as in the case of modelling horseshoe opening which was 5.5 m wide and 5.0 m high. The estimator was obtained from this modelling data.

3.2 Results from the synthetic 2D blind cases

In most of the synthetic 2D blind cases (1, 2, 3, 4, 7, 8 and 9) the algorithm performed well and results were found with minimal deviation. 5 % of mean noise (case 5) and 10 % mean noise (case 6) weakened the solution, but not more than by 10 %. Non-intersecting unknown joint set weakens the solution greatly (case 11) and intersecting unknown joint makes the problem unsolvable (case 10). Swapped instruments (case 12) cannot be solved. The cases 10-12 can be easily identified as false solutions graphically from measurement-estimate plots (Figure 1). The effect of noise is also clearly visible, but distinct.

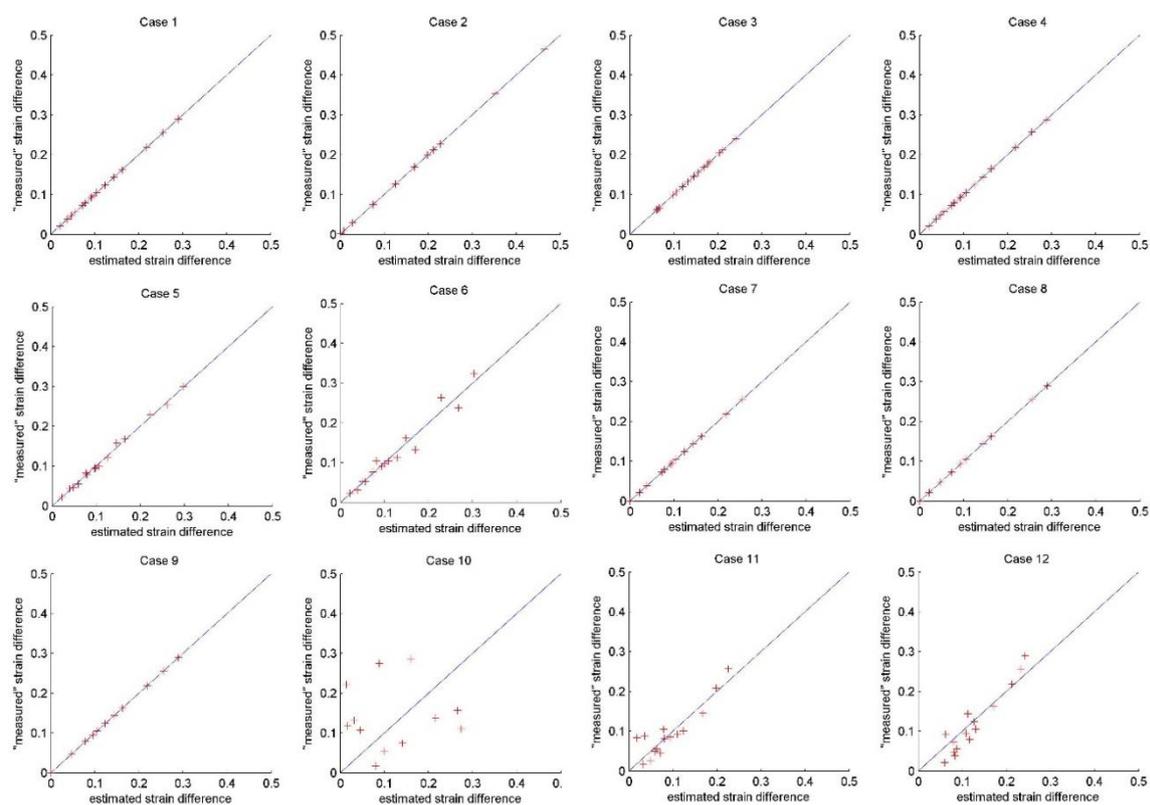


Figure 1. Modelled strain differences and estimated strain differences for the 12 blind cases.

4 IN SITU TEST OF THE METHOD

To test the method in real mining environment an experiment was planned to Boliden's Kylylahti mine, located in Eastern Finland. In the experiment, a simple 2D test site was planned and executed near ongoing excavation. The test site was selected due to its plane strain conditions. The monitoring is conducted far enough from the nonlinear rock deformations to enable use of linearly elastic model; however, plasticity still has a minor effect to the stress state change in large and it is not incorporated in the algorithm. Nonlinear rock mass change is also expected where the extensometers intersects with joints. At the test site area the rock mass is fairly homogenous and is not heavily jointed. The expectation was that the nonlinear changes in the measured area would be negligible.

4.1 Executed excavations

The purpose of the instrumentation was to track stress state changes caused by the excavation of the stope. The Kylylahti mine uses open stoping with delayed backfilling as a mining method. Both longitudinal and transverse stopes are used depending on the thickness of the ore body. At the test

site longitudinal open stoping was used because the stope is located at the narrow part of the ore body. The excavation geometries and modelled extensometer angles are shown in the Figure 2.

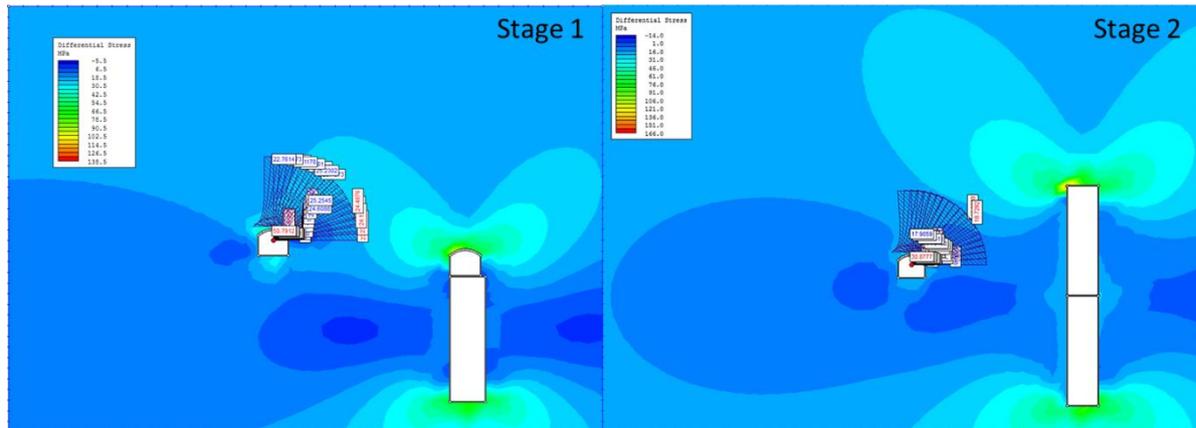


Figure 2. Modelled changes in mining geometry and modelled angles for extensometers. Stage 1 before mining of the target stope and Stage 2 after mining of the target stope. Presented in differential stresses ($\sigma_1 - \sigma_3$). Extensometers modelled for every fifth degree.

The excavation monitored in this study was located at level 322 at depth of approximately -410 m and the total mass excavated was approximately 10 000 tons (see Figure 2b). The dimensions of the stope are: height 25 m, width 9 m and length 15 m. The distance from the measurement site to the stope was approximately 30 m. Sequencing was used during the excavation of the stope.

The monitored level was not virgin thus mining had already started at the level. One stope behind the excavated stope had already been mined. Also the stope under the monitored stope was already mined and backfilled. The already mined stope was modelled as empty stopes due to the low Young's modulus of the backfill material. The mining continued after the target stope had been excavated and increased the plain strain conditions. The changes caused by the next excavation were also tracked.

4.2 Modelling of the experiment

The test site was modelled to find out the directions and magnitudes of the displacements and in order to enable efficient installation pattern for the extensometers. The 2D test site was modelled using 2D boundary element program Examine2D 8.0, in two stages (see Figure 2). In the first stage, the displacements caused by the earlier mining activities were determined. In the second stage, the total displacements caused by all of the excavations were modelled.

In the modelling phase the extensometers were modelled in every fifth degree from angles 0 to 90 degrees. Based on the modelling results the actual positions of the extensometers to be installed were decided. The first goal was to have representative instrumentation to enable monitoring of displacements to all directions. The second goal was to ensure that the displacements caused by the mining would be sufficient to be measured.

4.3 Modelled rock mass response

The modelled displacements were calculated by deducting modelled displacements of stage from modelled displacements of stage 2. The model showed that the displacements for the lower angle extensometer would be approximately two millimeters and for the higher angle extensometer approximately one millimeter. Most of the total displacements were caused by the horizontal displacement. This emphasized the requirement to install the extensometers to low angles.

4.4 Instrumentation

The selected location was instrumented using multi-point borehole extensometers to measure strain in multiple locations. Both of the extensometers were 20 meters long and were installed to angles of 20 and 50 degrees measured from horizontal. Also third extensometer location to 70 degree angle was planned but due to lack of grouting pump power it was not installed. The extensometers included six anchor points placed in every 3.33 meters. The installed extensometers are presented in Figure 3.

With the mine site lacking a wireless network connection to the surface, the real time monitoring was carried out using automatic dataloggers to read the extensometers. Sampling rate of four hours was used. The instruments were installed according to the instructions given by the manufacturer. Also possibility to use downhole installation for the extensometers was investigated but it was concluded to be not possible for this test site.

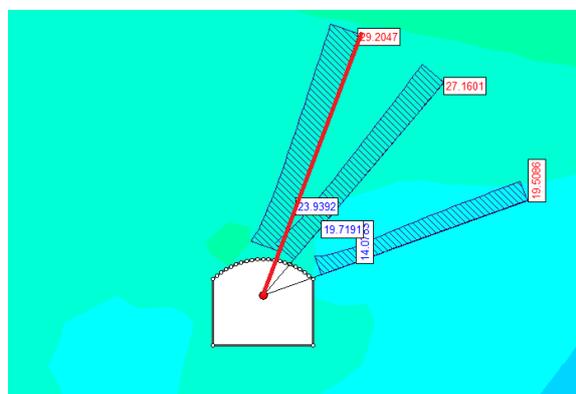


Figure 3. Extensometers planned to be installed. The not installed extensometer is shown with red color.

5 CONCLUSIONS

The algorithm was successfully developed and based on 2D and 3D synthetic blind tests it performs well in clean cases, noisy cases and missing data cases. The method has problems coping with joints and more effort is needed in rock mass characterization on site. For analysis of in situ performance in actual mine conditions, 2D models of Kylylahti mine stopes at -410 m depth were created and calculated. The test site was instrumented with extensometers installed to optimal locations based on the prediction modelling and the algorithm will be tested during summer 2015 based on the measurement results.

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