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Stress State Change Monitoring Using Displacement Change Measurements

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ABSTRACT
A method to back calculate stress state change was developed in Dynamic Control of Underground Mining Operations (DynaMine) research project. The purpose of this method is to provide real-time estimates of the stress state change caused by excavation. In this paper the method is evaluated with \textit{in situ} data analysis and using two-dimensional modelling. The method is based on linearly elastic modelling and multiple linear regression between the modelled engineering strains and measured engineering strains. The measurements were done at the Kylylahti mine and using data from Posiva’s ONKALO rock characterization facility as reference. The Kylylahti test site was instrumented with two 20 meter multipoint borehole extensometers. 2D modelling was used to analyse the test site conditions using both near field and far field models. The data obtained from the test site was used to track changes caused by an excavation approximately 30 meters from the test site. The resulting stress change estimates from both of the sites were generally too high. Possible reasons for the too high estimates are discussed and suggestions for future research are given.

KEYWORDS
Stress state change, Kylylahti mine, ONKALO, Real-time, back calculation, \textit{in situ} test, multiple linear regression, extensometer

INTRODUCTION
The objective of this study was to test stress state change estimation algorithm created in Tekes Green Mining program Dynamine project. The algorithm and its benchmarking have been presented in conference paper by Kodeda \textit{et al.} (2015). The motivation to create this algorithm was to develop easy-to-use and inexpensive method to monitor stress state change caused by mining activities. The method is based regression between linearly elastic modelling and displacement measurements. The regression in the method is formed with least squares method.
**IN SITU CONDITIONS**

The measurements were done at Kylylahti mine in Eastern Finland (Figure 1). The Kylylahti Mine is an underground copper mine with production of 700 000 tonnes of ore per annum. The mining method is open stoping with delayed backfilling. The test site was located at level 322 in depth of approximately 420 meters.

![Figure 1. Location of the Kylylahti Mine. (Ritala, 2015)](image)

The regional geology at the mine site consists five different geological zones: Outokumpu assemblage ultramafic rocks serpentine and soapstone (OUM), high temperature altered ultra-mafic rocks (OME), Kaleva assemblage metasedimentary rocks (KAL) and massive (MS) and semi-massive sulfides (SMS). The test site geology consists mainly of massive and semi-massive sulphides and high temperature altered ultramafic rocks. In Table 1 rock properties of different geological domains are presented. The rock mass properties are given in Table 1 and the selected modelling parameters in Table 2.

<table>
<thead>
<tr>
<th>Rock unit</th>
<th>UCS (MPa)</th>
<th>E (GPa)</th>
<th>v</th>
<th>(\rho) ((kg/m^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAL</td>
<td>155</td>
<td>60</td>
<td>0.35</td>
<td>2800</td>
</tr>
<tr>
<td>MS-SMS</td>
<td>140</td>
<td>85</td>
<td>0.32</td>
<td>3300</td>
</tr>
<tr>
<td>OME</td>
<td>95</td>
<td>90</td>
<td>0.32</td>
<td>2900</td>
</tr>
<tr>
<td>OUM</td>
<td>150</td>
<td>75</td>
<td>0.33</td>
<td>2800</td>
</tr>
<tr>
<td>Soapstone</td>
<td>35</td>
<td>35</td>
<td>0.32</td>
<td>2800</td>
</tr>
</tbody>
</table>
Table 2. Modelling parameters at Kylylahti Mine.

<table>
<thead>
<tr>
<th>Modelling parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major principal stress ($\sigma_1$)</td>
<td>30.8</td>
<td>MPa</td>
</tr>
<tr>
<td>Intermediate principal stress ($\sigma_2, \sigma_3$)</td>
<td>22.5</td>
<td>MPa</td>
</tr>
<tr>
<td>Minor principal stress ($\sigma_3$)</td>
<td>11.3</td>
<td>MPa</td>
</tr>
<tr>
<td>Elastic modulus ($E_m$)</td>
<td>29000</td>
<td>MPa</td>
</tr>
<tr>
<td>Poisson’s ratio ($\nu$)</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Uniaxial compressive strength (UCS)</td>
<td>110</td>
<td>MPa</td>
</tr>
<tr>
<td>Geological strength index (GSI)</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Material constant ($m_i$)</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Disturbance factor (D)</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

TEST SITE INSTRUMENTATION

The plan was to instrument the site with three 20 meter long extensometers. The chosen angles for extensometers were 20, 50 and 70 degrees. These angles were chosen based on preliminary model of the test site using a 90 degree sweep with 5 degree intervals to find the optimum angles. The preliminary modelling was done with Examine2D and the used parameters can be found from the Table 2. Modelling of the instrumentation site predicted displacement magnitudes approximately one millimetre along the extensometer. The chosen extensometers were multipoint borehole extensometers which included six measurement points each. The measurement points were placed evenly on the length of the extensometer. The displacement measurement is done at tunnel face with potentiometers. The measurement principle of the extensometers is illustrated in Figure 2. The potentiometer head (on left in Figure 2) tracks the amount of travel for each length and the differences are used to calculate strains for each interval.

![Figure 2. Structure of the extensometers. (Ritala, 2015)](image)

Finally, the test site was instrumented only with two extensometers due to technical difficulties and tight schedule. The final test site setup is shown in Figure 3. The installed extensometers were in angles of 20° and 50°. The 70° extensometer marked with red color was not installed. The detailed installation procedures are reported in Ritala (2015).
CONDUCTED EXCAVATIONS

In Kylylahti mine sublevel stoping with backfilling is used. The direction of the stoping varies by the thickness of the ore. The site area is located at the narrow part of the orebody where conventional sublevel stoping is used. The conducted excavation is shown in Figure 4. The stope under the excavation was already mined and backfilled but it was modelled as empty stope as the backfilling is a passive structure. The mining of the stope started in the end of December 2014 and ended in middle of January 2015. The total excavated volume was approximately 8000 m$^3$. The height of the stope was 25 meters and width 8 meters.

RESULTS

The results were calculated with the principles presented in conference paper by Kodeda et al. (2015). The basic principle of the method is to compare modelled and measured strains using multiple linear regression and superposition principle. As a result the method gives the two principal stresses and the direction of the largest principal stress. For more detailed discussion see Ritala (2015).

The changes in the beginning of the measurement period were small and barely within the region of the measurement accuracy. After the second stope at the level 322 was mined the displacement and thus the strains increased. Mining of the second stope strengthened the results gained from the two dimensional model by increasing the plane strain conditions. The results are obtained using the linear regression between
measured strains. Before final results are obtained the results are provided in three factors which present horizontal stress $\Delta \sigma_x$, vertical stress $\Delta \sigma_y$ and shear stress $\tau_{xy}$. The final results from the Kylylahti Mine in the principal stress plane (largest principal stress $\Delta \sigma_1$, smallest principal stress $\Delta \sigma_3$ and angle of largest principal stress direction $\theta$) are provided in Table 3 as stress state changes.

In the beginning of the measurement period only one of the extensometers measured strains. When both of the extensometers started provide results the fits between the estimated and the measured strains started to grow. In total the the changes in the stress state were as expected but the fits gained from the linear regression were not satisfactory. It also has to be noted that the fit between measured and estimated strains was really good in the last measurement but the change in the stress state was much greater than anticipated. The fits in measurements on 9th of March and 22nd of January are presented in Figure 5.

Table 3. Estimated stress state changes during the excavation of the stope. The results are representing the change from the original stress state.

<table>
<thead>
<tr>
<th>Date</th>
<th>$\Delta \sigma_1$ (MPa)</th>
<th>$\Delta \sigma_3$ (MPa)</th>
<th>$\theta$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.12.2014</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>31.12.2014</td>
<td>-2.2716</td>
<td>-15.7032</td>
<td>0.2181</td>
</tr>
<tr>
<td>1.1.2015</td>
<td>-2.2716</td>
<td>-15.7032</td>
<td>0.2181</td>
</tr>
<tr>
<td>5.1.2015</td>
<td>-3.1702</td>
<td>-18.389</td>
<td>5.487</td>
</tr>
<tr>
<td>12.1.2015</td>
<td>4.1221</td>
<td>-20.8734</td>
<td>30.6807</td>
</tr>
<tr>
<td>22.1.2015</td>
<td>5.066</td>
<td>-21.0964</td>
<td>32.7771</td>
</tr>
<tr>
<td>9.3.2015</td>
<td>54.5447</td>
<td>-54.0243</td>
<td>41.522</td>
</tr>
</tbody>
</table>

Figure 5. Regression results between estimated and measured strains. a) 9th of March and b) 22nd of January. The results from different extensometers are marked with different colours. (Ritala, 2015).
REFERENCE STUDY

Because of the unclear results obtained from the Kylylahti test site it was decided that already gathered and analysed data would be more beneficial for the study. A dataset from Posiva’s ONKALO rock characterization facility was received for further testing of the algorithm. This dataset was collected during excavation of new cavern next to an existing tunnel (Johansson & Siren, 2014). The 2D geometry is shown Figure 6. The change caused by the excavation was measured accurately and it was in a region that was sufficient for the code, both extensometers showing displacements of over one millimetre.

Also the rock types at the ONKALO test site are more suitable for the elastic analysis because they are more homogenous than the rock types affiliated with the Kylylahti mine measurements. At the Kylylahti mine one of the main concerns was that the rock mass was already heavily disturbed and fractured. At the ONKALO test site the excavations are done more delicately than at Kylylahti mine site due to their different use. The excavation monitored at the ONKALO test site is shown in Figure 6. The goal of the excavation was to excavate a maintenance hall for Posiva. The excavation was monitored from tunnel next to the maintenance hall to be excavated.

The displacements and temperatures from the ONKALO are shown in Figure 7. As can be seen from the figure the extensions occur within the first two months of the measurement periods. Thus it was decided that only this time frame would be included into the study. The Posiva data was analyzed in same manner as the data from the Kylylahti mine. The main difference between the two data sets was the amount of data points included into the model. The measurements done in the ONKALO were done with two extensometers both having three measurement points.

Figure 6. ONKALO 2D geometry before (left) and after (right) tunnel excavation.

Figure 7. Time frame of interest and extensions from the ONKALO test site.
The results from the ONKALO test site are presented in Figure 8. The greatest relative stress state changes occurred between 26th and 27th of October, highest step being change of over 20 MPa. As in the Kylylahti Mine when the extensions increased the fits between the measured and estimated strains improved. Example fit from 27th of October can seen in Figure 9.

![Figure 8. Results from the ONKALO test site. (Ritala, 2015).](image)

![Figure 9. The obtained result of the multiple linear regression for the ONKALO in 27th of October. The results marked with different colors are from different extensometers (Ritala, 2015).](image)

**DISCUSSIONS**

Both of the near field analysis, for the ONKALO and Kylylahti test sites, provided similar results. These predicted stress changes were too high to be reliable. On the other hand the algorithm was able to spot when the stress state changes occurred. In Kylylahti mine the high results may have been due to already disturbed rock mass. At
Posiva test site the measured displacement were more in line with modelled displacements and it is suspected that the used rock mass modulus at Posiva is generally or at the excavation damage zone too high. Currently, the method is not usable in mining environment. The most important factors impacting to the usability of the method are:

- Over estimated modelling parameters such as Rock Mass Modulus and Poisson´s ratio,
- Earlier mining activities, which cause disturbance of the rock mass,
- Displacements or strains caused by plastic deformation,
- Using of linearly elastic model,
- Measurement inaccuracies,
- Readout inaccuracies.

Earlier activities at the Kylylahti Mine test site were probably the main reason why the results were inconsistent. The rock mass was already disturbed and some of the deformations had probably already occurred. The extensions measured at ONKALO were more in line with the modelled extensions. Also the progress of the excavation can be tracked from the measurement data. This suggests that the rock mass is more intact than at the Kylylahti mine.

For further studies these factors have to be considered. The next step for this study would be to replicate the 2D test site with improvements. These improvements would be the documentation of the boreholes, using a model capable of dealing with plasticity, more precisely investigated rock mass at the area, increasing the amount and variety of instruments and comparison study using CSIRO hollow inclusion cell.

Documentation of the boreholes is vital to gain knowledge of the location of the joints penetrating the borehole. Also changes in rock mass or rock type along the borehole length are important to know. These factors impact how the rock mass is acting during the excavation and where the stress state changes occur and thus the rock mass displacements.

During this project it was noted that rock mass modulus was overestimated in both locations. It has to be noted that rock mass modulus is the key component when converting strain measurements into stress state change. The overestimation may have been due to conventional methods used to determine the rock mass modulus. When using the rock mass modulus to determine the stress state change it is preferred that the rock mass modulus is determined from in situ experiments.

In this project 2D boundary element method software was used to model the rock mass behaviour. With this software the rock mass is characterized with only two parameters, Poisson’s ratio and rock mass modulus. Lately new methods to model rock mass have been developed. Modelling approaches such as presented in article by Ivars et al. (2011) would suit the algorithm well. The synthetic rock mass approach presented in the article is designed for scales from 10 m to 100 m. This suits well for the purposes of this type of study. The synthetic rock mass combines discrete fracture network (DFN) with intact rocks bonded particle model. The cons of this type of modelling would be increased time to create the model and the increased calculation time of the model. The model would also require more input data of the fracture network and joints.

**CONCLUSIONS**

In its current development stage the method is not suitable for mining environment. On the other hand using of strain measurement data to estimate stress state change should be investigated further because this type of knowledge is useful especially when dealing with deep underground mines. As for now the real-time solution for the stress state change monitoring is possible because the calculations used are fast and can be easily automated.
ACKNOWLEDGMENTS

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REFERENCES


