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Abstract

Underground mines rely on point stress measurements, which are limited both in time and in space. Developing a stress monitoring system that can provide real-time information about the surrounding rock mass stresses is seen as highly prospective. Mines could quantify the level of rock mechanical hazards and track stability of the excavations. A method for real-time stress change estimation was developed at Aalto University. The method uses strain measurements, which are obtained using extensometers and inverse calculation of stress change using superposition of unit stress responses. It was tested in Boliden’s Kyllylahhti mine. Aalto University developed guidelines for risk assessment in underground mines that can utilize real-time rock stress input in order to quantify the level of geotechnical hazards. The long-term goal is to develop a concept for real-time monitoring and risk assessment in underground mines. The objective of this paper is to summarize the preceding research and to investigate how the real-time in situ stress data can be used for real-time risk assessment and ground support optimisation in underground mines. The key concepts are introduced and the required changes to the process with real-time data are described. An example from Kyllylahhti mine is presented as an example use case. The current state, required changes, advantages and difficulties with the current approach are discussed. Finally, based on the observations, suggestions for future research are given.

1 Introduction

In recent years the authors have developed mining safety research at Aalto University in two projects. The first is a project for the iMine (Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future) under the 7th framework programme of the European Union, where a formal geotechnical risk management guideline was developed to tackle the geotechnical risks in underground mines (Mishra, 2012; Mishra & Rinne, 2014; Janiszewski, 2014; Janiszewski et al., 2015). In the second, Dynamine project under Tekes Green Mining programme, the objective was to create a real-time rock mechanical monitoring concept for the mining industry (Ritala, 2015; Ritala et al., 2016; Kodeda et al., 2015). The goal was to increase the safety of deep underground mines where large changes in the stress field due to stope excavations can cause significant risks. In this paper the two concepts, the guidelines for the developed geotechnical risk management and real-time stress change monitoring, are joined to study the potential to provide a solution for real-time risk assessment and ground support optimisation in underground mines. The long-term goal is to develop a concept for real-time monitoring and risk assessment in underground mines. The objective of this paper is to summarize the preceding research and to investigate how the real-time in situ stress data can be used for real-time risk assessment and ground support optimisation in underground mines. The current concept is based on stress state change estimation algorithm based on back-calculation of measured strains. The real-time monitoring is able to provide feedback about the success of mining sequencing and sufficiency of ground control methods. By monitoring the actual change,
the design and the sequencing of the stopes can be turned into an iterative process. With the real-time monitoring, it is possible to increase the safety of underground mines if the stress changes cause risks.

In the geotechnical risk management (Figure 1), the geotechnical hazard potential (GHP) is an evaluation performed using an indicative ranking of mining operations based on the potential it has in causing a geotechnical hazard. Modified Barton’s Q value is used to classify rock mass competency into 5 classes ranging from ‘very good competency’ to ‘very poor competency’. The GHP classification system can be translated into a preliminary risk assessment to justify a formal hazard-specific risk assessment for an area to predict and prevent geotechnical accidents. Next, the geotechnical risk assessment is executed to identify and mitigate hazards before they pose risk to the working environment. The risk assessment process has been divided into five phases:

1: Outlining the scope of risk assessment
2: Identification of hazards within the scope
3: Evaluation of the likelihood of hazard
4: Assessment of the consequences (exposure to hazard)
5: Ranking the risk to formulate a strategy of risk reduction.

Figure 1  Geotechnical risk management flowchart (Janiszewski et al., 2015)
If the level of risk is known for a particular location, then mitigation measures are selected and implemented in order to reduce it to an acceptable level. Reliability assessment aims at estimation of the degree of confidence the mitigation measures provide against the risk. Monitoring is an important part of geotechnical risk management, as it provides information that can be used in quantification of hazard probability during the risk assessment process, and is used for review and evaluation of the reliability of mitigation measures. Geotechnical risk management is a cyclic process, where all activities are repeated systematically until all risks are reduced to an acceptable level. Communication and consultation of results with all involved partners is crucial in order to facilitate good transfer of knowledge and hazard data through different stages of mining.

There are several geotechnical hazards that are caused by the extensive deformation of rocks. Rockfall is an uncontrolled detachment and movement of rock fragments into the excavation. Rockfalls cause 24% of fatal accidents in underground mines worldwide (MacNeill, 2008). Real-time monitoring of the movement of excavations can be used for evaluation of rockfall hazard. An example of such system has been presented by Vogt et al. (2010), where an AziSA standard is applied for rockfall early warning systems in South African mines. Data from measurements of excavation closure is combined with thermal images and acoustic sounding tool data to produce a rockfall risk map for different areas in the mine. Another type of geotechnical hazard, where monitoring of rockmass conditions is used for hazard assessment, is rockburst, a violent failure of rock due to high concentrations of stress around the excavation. It is often present in deep mines in hard and brittle rocks. High rockburst hazard is associated with high rock stress conditions and rapid changes in stress which may lead to a seismic event. Rockfalls and rockburst can cause failure of ground support and damage the excavation, hence resulting in loss of its functionality.

Use of the real-time monitoring is best accompanied with the observational method that allows a controlled way to adapt to the geotechnical behaviour. The method, first suggested by Terzaghi and defined later by Peck (1969), is based on establishing plans in advance, monitoring the ground behaviour during excavation and then executing contingency actions to select the ground support based on the measured ground behaviour during excavation. In this way the conservativism of the plans can be decreased while still achieving safe and economical ground support. The relevant hazards are identified in the planning stage using the geotechnical risk management system. The combination of the geotechnical risk management system, observational method and real-time monitoring will rationalize ground support measures in challenging conditions.

2 Real-time risk management

The philosophy behind real-time risk management and monitoring of rock mass can be described by the Data-Information-Knowledge-Wisdom (DIKW) hierarchy proposed by Ackoff (1989). ‘Data’ represents raw measurements and ‘Information’ is the data, which acquires meaning through identified connections and relationship with other data. ‘Knowledge’ is the collection of information, which enables understanding of patterns. ‘Wisdom’ is created by applying the knowledge through evaluated understanding and represents the decisions made by humans. The DIKW hierarchy is plotted on Figure 2 as a chain of increasing connectedness of links in the chain (Y-axis) and our understanding of the process (X-axis). Knowledge is all data and information from the events that took place in the past, and wisdom represents the predictions made about future events. In relation to real-time monitoring, the DIKW hierarchy illustrates how increasing the collection of information by more frequent recording of data can be used to create more knowledge and make better predictions about future events and their effect on the performance of excavations.
Risk is a product of the probability of a hazard to occur and the consequences (or severity) that might arise if the hazard takes place. Some risk assessment methods include the vulnerability of an excavation in the probability part of the risk equation, which determines its proneness for damages due to large ground movement and deformations. An example of vulnerability concept is the Rockburst Damage Potential (RDP), which is an empirical index proposed by Heal et al. (2006) for estimation of rockburst damage, and is implemented in the Mine Seismicity Risk Assessment Program. The RDP relates the peak ground movement and several factors, such as stress conditions, ground support capacity, excavation span and geological structure, in order to estimate the susceptibility of an excavation to be damaged during a rockburst event. The consequences part of the risk equation is sometimes represented as the exposure to the hazard to express the quantity of assets that are at risk, which directly correlates with how severe the hazard can be. Given the real time measurements deal with specific risks, the exposure cannot be ignored. According to Woodward & Wesseloo (2015) the influence of stress change is considerable and has a big impact on the probability of a rockburst to occur:

“Elevated rates of seismicity in a mining environment are commonly observed following significant changes in stress conditions, lasting in the order of hours to days.”

Access to real-time information about changes in stress state can provide an indication of elevated seismicity expected to occur and can be a valuable tool for monitoring of the vulnerability of an excavation. Such knowledge can be used in early warning systems and entry protocols to lower the risk in underground mines. Real-time monitoring of rock mechanical conditions can be a valuable tool for proactive maintenance of underground excavations and adjusting reinforcement design during mining operation. Changes in the rock stress field induced by mining can be anticipated and their impact on continuation of operation can be evaluated in real-time. Furthermore, adjustments to mine design can be done based on the results from monitoring, for example selection of favourable orientation of the excavation with respect to the stress direction in changing mining environment.

Real-time measurements eliminate the data acquisition time and therefore reduce the data analysis time. In principle, any geotechnical accident should give yielding signs but they can be missed if the prominent events happen between conventional monitoring intervals. Site specific hazard likelihood assessment models can be built when historical data is available. These models can be then automated to continuously evaluate real time measurements to provide a live view of the hazard states such as stress and seismicity. This reduces chances of human error and thus ensures high reliability. Quick reaction time ensures that the maintenance of an underground opening is non-invasive and corrective actions such as additional reinforcements are done before the failure symptoms actually occur. With the advancement in equipment
automation in deep underground mines, the preference and extent of wireless network coverage is increasing. Existing instrumentation such as extensometers and geophones can take advantage of the existing network infrastructure to transmit real-time data to a central data repository. Even in mines without a wireless infrastructure the need for an effective warning system becomes justifiable with depth and increasing geotechnical risk. Risk can be evaluated in real-time and dynamically with continuous assessment of information. High risk mining areas can be even equipped with a safety-state warning system.

3 Risk assessment process with real-time data

Based on the guidelines developed to carry out Geotechnical risk assessment (GRA), GRA focuses on four primary forms of industry-wide risk assessment methods, namely Workplace Risk Assessment and Control (WRAC), Failure Mode and Effect Analysis (FMEA), Bow Tie Analysis (BTA) and Fault Tree – Event Tree Analysis (FTA – ETA) (Mishra et al. 2014). These 4 methods are misnomers as they primarily provide a framework of arriving at various possible hazards that can lead to a top event but not the likelihood of it happening. These methods help answer “What can lead to an accident?” but do not answer the crucial question of “Will the accident happen?”. Real-time measurements help determine the likelihood of hazard and can be used with any of the four risk assessment methods. Based on the GRA guidelines, the Fault Tree – Event Tree analysis is the preferred choice of risk assessment because it uses quantitative probability of occurrence values which are data driven.

Fault Tree Analysis (FTA) is a deductive method of hazard analysis where a hazardous event is evaluated downwards to identify all the possible causes leading to an event (Iverson et al. 2014). This includes combinations of hazardous conditions which lead to an accident. FTA is comprised of 3 components. First is ‘Top event’ which is the principle accident in consideration such as roof fall. Second is ‘Hazards’, which are the conditions which lead to an accident. Third is ‘gates’ which are Boolean logic operators such as ‘and’ and ‘or’ which imply if all or either of the hazards are needed to be present to cause the accident. This process is done till the primary hazards are identified. Probability of each primary hazard is calculated, which in turn gives the likelihood of the accident. Event Tree Analysis deals with the probability of the various consequences of the top event. Event tree does not comprehensively quantify the full severity of a consequence but helps to narrow down the various possibilities.

An effective risk management system must integrate all available information sources to form the backbone of a robust intervention system. This is done by evaluating all possible failure modes of a system. The analysis is done till all possible rootcauses (leading eventually to the incident/accident) are identified. This exercise not only aids in a detailed probabilistic calculation but also presents a visual map of various ways in which a system can fail and different components that contribute to it.

A hypothetical example is considered in Figure 3 showing a basic fault tree analysis where the top hazard is stresses exceeding the support capability. In this example, the root causes identified are incorrect support design, inferior support quality, incorrect support installation which can lead to undersupporting of a mining area. The other causes identified are unexpected stresses created by incorrect mining sequence and/or blasting/seismicity induced stresses. Once all the root causes or primary hazards are identified, the probability of them occurring is evaluated. Where data is available, probability can be evaluated using historical occurrences. If a mine uses a rigorous quality assurance/quality check (QA/QC) programs and the historical data suggests that less than 5 out of 100 samples were substandard within a given period, the probability of a support being of inferior quality is set at 5%. Incorrect design probability is a combination of quality and extent of data used for the design and the competence of the person/team responsible for the design. While periodic measurements of modeled vs. measured data can provide an estimate of instances a mine gets the design wrong, real-time measurement can provide the exact time when the deviation occurs and prevailing circumstances that led to it. In this example the assumption made is that the chance of poor design is 10%. Chance of incorrect installation can also be obtained using historical data for a mine with QA/QC procedures in place. Additionally, real-time measurement of deviation and follow up investigation of affected area can also help reduce installation errors. The assumed probability of incorrect installation in
this example is 5%. Similarly, historical data can help establish how often does the mine deviate from planned mining sequence, and real-time measurements can help to establish the impact of blasting on the stress state of the mining area. The probability of incorrect mining sequence and blasting/seismicity induced stress change beyond support capacity is assumed to be 5% and 10% respectively. With the above probabilities, the likelihood of a poor support evaluates to 18.8% while probability of mining induced stress exceeding support capacity evaluates to 14.5%. This results in a net probability of the hazard of 31%. However, a real-time measurement of geotechnical parameters can help build an early warning and intervention system. If such a system having a 10% chance of failure between planned maintenance is put in place as a deterrent, the likelihood of the hazard being realised is reduced from 31% to 3.1%. Therefore, with real-time monitoring in place, trends of deteriorating geotechnical conditions can be continuously evaluated and mitigating measures can be put in place well in advance thus reducing the risk of an accident to an acceptable level.

Figure 3  Fault Tree Analysis (FTA) showing hazards leading to stress exceeding support with real-time monitoring as a deterrent

4  Decision making with real-time data

Data processing and analysis can be grouped into three categories depending on the resources used and the complexity of the model.

4.1  Direct correlation between failure and monitored data

First approach uses the direct correlation between failure and monitored data when substantial historical data is collected with similar rock properties, which are then used to assess a new region. Information of rock properties at the time of failure or near failure should be available to build a direct correlation between information being measured and reported, and hazard being assessed. For instance, if sufficient evidence is available to show that when displacement measurement from extensometers is $x$ and/or seismic reading from geophones is $y$, it leads to rockburst in level $z$. Given the variability in rock properties, the ideal process is to set various levels of thresholds to warn if risk is low, moderate or high. This method does not require any data processing and local rugged computers can also be used to change the risk status.
of a mining area. One of the key disadvantages of this is that it only looks at the symptoms of failure and does not try to evaluate the state of underlying hazard such as high stress. Given the impact of mining induced variables such as blasting, sequence of excavation on underlying hazards, it is necessary that such a warning system works with high factor of safety.

An example of this approach is the observational method, which is often credited to Peck (1969), although his paper actually is more of a synthesis of a practical work approach called the learn-as-you-go method, which was formulated and developed by Terzaghi during the preceding decades. The benefit of the observational method is the possibility to use measurements to reduce the amount of conservatism caused by geotechnical uncertainties. Peck’s definition has eight steps: exploration, assessment of most probable and most unfavourable deviation, most probable design, selection of quantities to observe, calculation of quantities under unfavourable conditions, selection of course of action for every foreseeable deviation, measurement and evaluation, and modification of design to suit conditions.

The Eurocode 7 (EN 1997-1:2004) implementation of the observational method is straightforward: establish limits of acceptable behaviour, assess range on possible behaviour, plan monitoring, plan contingency actions, monitor. It discards the most probable and most unfavourable approach, but otherwise it is an extension of the method as described by Peck. Spross (2014) criticises the observational method approach presented in EC7, pointing out that it is unclear how to determine acceptable behaviour, the approach apparently lacks a safety margin, the predictability of the control parameter is neglected. He suggests that methodology should be developed to assess the safety of structures built using the observational method, long-term extension of the method for monitoring of existing structures and a link to probabilistic design of structures.

To use the observational method in conjunction with real-time data, some additions to the Eurocode procedure are needed. First, preliminary modelling is used to select locations for the sensor network. Then, detailed modelling is carried out for each sensor to produce unit responses. Multiple linear regression is used to solve the corresponding stress state. These stress states are then compared to the corresponding ground behaviour.

The ground behaviour is numerically analysed and the acceptable limits for the local stress state are stored. Next the unacceptable states are analysed for damage extent and damage rate (e.g. strain rate). Here the risk assessment is in a key role. Sufficiently small and slow damage allows for contingency actions to be put into place. Finally the unacceptable limit is stored. Traffic lights can be used to illustrate the purpose of the three areas and two limits: the green area is when the stress state is acceptable, yellow area implies that contingency actions must be installed and red area indicates failure.

The possible ground behaviour is split into categories. In the green category we have the predetermined and expected design solutions. In the yellow category we have the remedial and contingency actions. The red category implies unavoidable damage. The decision making process is automated. The sensors transmit the readings at regular intervals, the inversion is carried out and the resulting stress state is compared to the behaviour categories. If the green limit is exceeded the site engineer is immediately informed and the system recommends the contingency action appropriate. The reaction time and the installation time must be taken in account. If passive reinforcement is used, the activation deformation must be calculated to avoid collapse (too late installation) and failure of the reinforcement (too early installation). If the yellow limit is exceeded, the workers in the area are evacuated and the access to the area is prevented. This can occur for example if the strain rate exceeds the stable limit.

4.2 The use of predefined algorithm to evaluate underlying hazard

Second approach is based on evaluating correlation between monitored data and underlying hazard. This is carried out by subjecting monitored data to predefined algorithms to arrive at the state of the underlying hazard. An example of this approach is a method developed at Aalto University during the Dynamine project, where solution for real-time stress state change tracking was tested (Kodeda et al., 2015; Ritala, 2015; Ritala et al., 2016). The solution for stress state change tracking is explained in more detail in article.
by Kodeda et al. (2015). The basic principle of the solution is to measure strains with extensometers and then to compare the results to modelled strains. Through this statistical comparison the stress state changes can be solved. The analysis method created can be used to create threshold values for ground control management purposes.

The test was done in two different locations at Kylylahti mine site during 2015 (Ritala, 2015; Ritala et al., 2016). The test sites were instrumented using multipoint borehole extensometers (MPBX). The first step of the instrumentation was to model the test site area with future excavations to achieve optimal placement for the extensometers. The area was modelled with Examine2D. It was considered to be important that the extensometers would be placed in the areas where most of the stress-driven strains would occur. Second, the MPBXs were installed and new model based on the locations of the MPBXs was created. Third, the mining progressed to the next stope and the strains caused by the mining were measured. Fourth, the measured strains were compared to modelled strains and the stress state change was estimated.

The survey period at the Kylylahti mine was not sufficient for ground control risk management purposes and to create thresholds as mentioned in section 2. Longer measurement periods and multiple measurement locations are required for creating knowledge of behaviour of the support system during different mining sequences. With constant measurements threshold can be created. As said in the introduction, the creation and usage of thresholds is an iterative process. It is also important to instrument the site as early as possible to detect any changes in the early phase of the local mining sequence. The second test site at Kylylahti mine was considered to be practically useless due to late start of the monitoring and too high changes to be caused by elastic deformations. Although the risk of failure was considered to be high with the second test site, it was chosen to be monitored due the lack of alternatives. It was concluded that the modelling methods used were not sufficient enough to draw conclusion between modelled and measured strains. It was suspected that the rock mass was already highly damaged when the measurement period started.

The main results of the tests are presented in Ritala et al. (2016). The main conclusion of the results was that the method can track the changes but the results were of wrong magnitude. It was also concluded that the method is sensitive for plastic deformations. An example of the final estimated stress state changes is shown in figure 4.

![Figure 4](image.png)  
**Figure 4** Example of estimated stress state change at Kylylahti mine (Ritala, 2015)

Although cablebolts were not used in Kylylahti test site, for the purposes of ground control the usage of cablebolt extensometers is encouraged since cablebolt extensometers can also be used to give information about the loads generated to the support system. This information can be used when evaluating the
sufficiency of support, especially if the support is monitored in multiple locations. The measurement devices used and the solution for stress change are eligible for real-time risk management tools. The extensometers can be measured once per second if necessary and the stress state change algorithm can solve the stress state change from the measurement data approximately in one second. With wireless network the delay from observing the breach of threshold value to receiving the information is measured in seconds.

For ground control purposes thresholds can be created for the stress state estimation method. The first step of creating threshold values is to simulate the area of interest. The simulation method has to be based on the geological conditions. In homogenous geological conditions simple simulation methods, such as boundary element method, can be used. With complex geological conditions, more sophisticated modelling methods have to be used.

The second step of the process is to plan the instrumentation of the site. In the planning phase two important factors have to be considered. First is the geometry of the site to be instrumented. In more complex geometry more data points are required to achieve full impression of the strains and thus about the stress state changes around the area of interest. The second factor to be considered is the geology. If the area has discontinuity, such as loose interfaces between different rock domains, the areas near these points have to be monitored more comprehensively to understand their impact on stress paths.

After the instruments have been installed and the mining sequence has continued, the data received can be interpreted. After the interpretation it is vital that the data used is gathered into a database where it can be later used when the mining continues. By grouping the data into different rock mechanical zones the collected data can be used for iterative process and the knowledge of the behaviour of different rock mechanical zones are increased. The iterative process of using real-time measurements as risk management tool is illustrated in Figure 5.

![Figure 5: Iterative process of using real-time measurements as mine-wide risk management tool.](image)

4.3 Predictive Analytics

Third, the Predictive Analytics is used to recognize abnormal conditions. Predictive analytics has been popularized with the advent of ‘Big Data’ and ease of data acquisition. The principle modelling technique in predictive analytics is called Similarity Based Modelling (SBM). SBM monitors all related parameters to identify patterns. From the pattern, an estimated behaviour of each parameter is generated (Gilboa et al. 2011). A central processor then compares the difference between the real-time and modelled parameter known as residual. If the residual value deviates from predetermined empirical thresholds, the system can then look at all the other related and non-related parameters that changed to evaluate what could have caused it. The advantage of such a system is that it can monitor very small residual variations and do iterative calculations to suggest possible causes. It can help gain better insight into data and find correlation
between parameters that were previously thought to be independent. The biggest disadvantage of the system is that it is data intensive and multiple parameters need to be monitored in real-time to get better estimations. However, with the increase in underground instrumentation and deepening mines, it has potential to be a tool for decision making.

5 Discussion

If rock mechanical conditions are monitored and assessed in real-time, the risk management procedure can be enhanced significantly. However, the emphasis should be put on analysis and interpretation of measured data in order to improve the understanding of interactions between rock stresses and underground excavations. The hazard potential of a particular mining area can be updated constantly and the risk assessment procedure can be initiated anytime, especially if the hazard level exceeds the pre-set limit. All mitigation measures can be monitored in real-time by continuous reliability assessment. The real-time risk management should be implemented in decision support software with user friendly graphical interface to help in the review, communication and consultation of risks.

The DIKW principle (Ackoff 1989) can be used for revision of ground support design. The understanding and connectedness of the whole process increases with the monitoring in place. In underground mines the rock stress is one of the uncertainty components in support design. Better knowledge about stress state and its changes can help to increase the design confidence level, and make better predictions about support performance in the future. Furthermore, uncertainties are also present in implementation of ground support. One of the measures to deal with uncertainty in ground support implementation is to monitor its performance and effectiveness. The latter can be done by observations and measurements, such as closure meters or extensometers. Collected data is then used for revision and optimisation of the support (Dunn, 2013).

In its best the real-time monitoring system is able to reduce the unnecessary conservativeness of the support system while increasing the safety due to monitoring and fast reaction capability. Also places with unforeseeenly high seismic activity can be identified based on the increased stresses and additional reinforcement can be installed in advance.

6 Suggestions for future research

It has already been established that the continuum-discontinuum property changes around the mining stopes are too large to be ignored (Ritala et al., 2016). Geophysical non-intrusive methods are required to observe the property changes inside the rock domain. The four biggest open questions are:

- How can the excavation induced changes be transformed into rock mechanical parameters?
- How to take in account rock mass damage, plasticity and jointing during the inversion procedure?
- How to translate the measured rock mass response into geotechnical risk?
- How to carry out on-line risk assessment covering the entire mining area?

The current formulation (Kodeda et al., 2015) is linear and cannot account for rock mass damage. It may be possible to add mining sequencing and rock mass damage. If plasticity is added without sequencing, the end result may be unrealistic due to incorrect stress path. Joints are easily added given that their locations and mechanical properties are known. How to sample the rock joints and how to upscale the results is unclear, but fortunately there are already active research addressing these issues (Uotinen et al., 2015, Iakovlev et al., 2016, Sirkiä et al., 2016).

Fracture mechanics modelling can be a key to solving how the damaged zone propagates and describing how the mechanical properties of the rock mass degrade. It also connects well with the seismic predictions both with emission location prediction and with intensity studies. After the acoustic emissions counts exceed a certain threshold, the sensor array can no longer track the locations or receive the signals through
damaged rock. Fracture mechanics modelling can be used to extend the sensor arrays and simulate the observed events forward in time.

After the method development, suitable equipment selection and a review of the sites available, the system should be installed in an active mine to test its performance in in-situ conditions. This site should be fairly clean of unknown abrupt changes in geophysical and rock mechanical parameters. It is also vital that the measurements are started as early as possible to ensure that no information of changes in rock mechanical conditions is lost. The proximity to an active mine stope would be beneficial to improve the signal to noise ratio. The installation time should be before the mining passes the area of interest and the sensors should be allowed to stay long after the mining activities have stopped to detect any long term effects (e.g. creep). The selected and instrumented mine should be periodically monitored and the data continuously retrieved and saved off-site to ensure partial recovery in case of sensor loss. Based on previous experiences for Kylylahti mine, we expect to lose up to half of the sensors during the stope excavations. This is in reality an operating mine and it also provides a way to measure the minimum sensor threshold for the method solvability. Less sensors mean more noise, however this can be compensated by sampling over time.

7 Conclusion

The long-term goal is to develop a concept for real-time monitoring and risk assessment in underground mines. In this paper, we have introduced two preceding research programmes I2Mine and DynaMine and merged the concepts. The first is a classification and risk assessment system for geotechnical risks and the latter produced an elastic method for in-situ stress determination based on strain measurements. We have described real-time measurements and decision making process, reinforcement design using observational method and how to use real time stress estimation as a risk management tool. It can be concluded, that the concepts merge well together, but there are a lot of details to be described meticulously and the methods used need to be described explicitly. We have expressed our suggestions for future research. The most important research need is a successful active mine instrumentation and integration.

We have described a concept for real-time risk assessment and ground support optimization in deep mines, where stress induced problems may occur. Geotechnical hazards potential is first evaluated and geotechnical risk assessment is then defined. Real-time in-situ stress data can be used in conjunction with precalculated reinforcement and contingency actions as a basis for ground support optimisation. For the monitoring displacement measurement devices (e.g. extensometers) are best suited from elastic to cracking rock and acoustic emissions or seismicity measurements for damaged rock calculations. The proposed method works best when installed close to mining activities at sufficiently early state to pick up the stress changes induced by the mining process.

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