Mishra, Ritesh; Janiszewski, Mateusz; Uotinen, Lauri; Szydlowska, Martyna; Siren, Topias; Rinne, Mikael

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Geotechnical Risk Management Concept for Intelligent Deep Mines


Aalto University, School of Engineering, Department of Civil Engineering, Rakentajanaukio 4, 00076 AALTO, Espoo, Finland

Abstract

Deep mining, driven by the increasing need of the sustainable use of mineral resources, yields a chance to exploit untapped resources. Nevertheless, large depths remain challenging and complex environment, posing geotechnical risks such as stress driven damage. The violent damage mechanisms in deep mines are spalling and strainburst in their most severe forms. Real-time monitoring can not only assist in preventing a failure, but can also assist in post failure mitigations. It can help identify the possible systemic failure of adjacent areas and can therefore help in evacuating people and machinery from these areas. The long-term goal is to develop a real-time risk management concept for intelligent deep mines. The objective of this paper is to summarize the outcomes of FMine and DynaMine, formulate a risk concept suitable for real-time analysis and to produce a tangible measure of the risk levels. In this paper the Fault Tree – Event Tree methodology is proposed and an example is worked out using strainburst as an example risk case. The proposed methodology seems to work well and using a scenario with both property damage and ore loss, the risk expressed as financial consequences multiplied with probability drops from €88,000 to €11,000 corresponding to a ~80% reduction in risk. The financial consequences together with the associated risk level can be expressed visually using a modified FN graph with financial loss on x-axis and probability on the y-axis. The developed geotechnical risk management concept suits the need of semi-automated or fully automated risk management. It would fit well in the analysis stage of the raw data and would produce a stress state change, which could be used as input in the risk management chain for intelligent deep mines.

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Keywords: Deep underground hard rock mines; risk assessment; rock stress; real-time data; inverse calculation

1. Introduction

The mineral resources are limited and mines are slowly expanding to tap into deeper deposits. With the increase of depth the transport costs and rock support costs increase. Massive extraction induces stresses and triggers seismic events. Failures in high stress conditions can have violent nature that aggravates mining conditions, threatens

* Corresponding author. Tel: +358-469-403-417.
E-mail address: ritesh.mishra@aalto.fi
the mine stability and increases working hazards. The violent damage mechanisms in deep mines are rock spalling and strainburst in their most severe forms [1, 2]. Strainbursts are considered the most common rockburst type in deep underground excavations [3]. Typical indicators for high probability of strainburst are: increased depth of mining, contrasting rock types (e.g. hard and brittle rocks vs. weak and yielding), drill hole behaviour, geological factors (e.g. faults, fractures), the increase of rock noise, large excavations, sudden change in cross-section area, and the increase in microseismicity [4]. The severity of the failure depends on the ratio of far-field maximum stress ($\sigma_1$) and the short-term unconfined compressive strength of the rock ($\sigma_c$) [1]. Less violent and energetic spalling can start to occur when $\sigma_1/\sigma_c > 0.2$ [1]. In mining conditions, it might be hard to recognize the difference between progressive spalling failure and violent strainburst as both cause a clear notch in a tunnel perimeter and can induce seismic event that can be recorded only if a mine is equipped with a microseismic network. Risk management tools and guidelines are essential to maintain safe and economically feasible extraction in the harsh underground environment, but they still need improvements. One opportunity identified here is the development of the real-time geotechnical risk management systems. The philosophy underlying this concept can be expressed by the Data-Information-Knowledge-Wisdom (DIKW) hierarchy introduced by Ackoff [5]. The author considers data as raw measurements, from which information is derived. Processed and analysed data is used for identification of data relationships that contribute to understanding. Understanding of data patterns and processed information provides knowledge. On the top of the DIKW hierarchy there is wisdom that represents the decision-making based on the knowledge gained. The Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future (I'Mine) project running under the 7th Framework Program of the European Union produced useful tools that reflect the abovementioned hierarchy. One of them that aim at use of the real-time data is the Dynamic Intelligent Ground Monitoring Internet Network (DIGMINE) capable of stress and seismic near-to-real time measurements and another is the Geotechnical Risk Assessment (GRA) guideline developed to tackle the geotechnical risks in underground mines [6, 7, 8]. In this paper the review of these is given and an expansion of the GRA with the outcome from the Dynamic Control of Underground Mining Operations (DynaMine) project is proposed. The paper discusses the use of financial parameters as means of measuring tolerable and intolerable risk. With the use of Fault – Tree, Event Tree and F – N Diagrams [9, 10], a conversion of geotechnical risk into monetary values and comparing it with pre-set financial targets is proposed. This knowledge can then be used to support a decision-making process for strainburst risk management in underground mines.

2. Geotechnical real-time risk assessment and risk management tools

The risk management methodology in the burst-prone ground has to be suited for challenging geotechnical conditions so that the reduction of high geotechnical risk will receive more attention. Designs best suited for geomechanical characteristics of the site, which will lower the geotechnical risk, should be prioritized, rather than highlighting production and cost constraints [11]. The decision-making in such conditions should be a link between the outcome of the specific strainburst risk assessment and the general mine project risk, and it must be based on a realistic target of the acceptable level of risk specified by mine management [12].

The DIGMINE platform (Dynamic Intelligent Ground Monitoring Internet Network) is a new real-time Global Stress Monitoring concept introduced by INERIS in 2015 [13]. New methodologies of stress and seismic near-to-real time measurements employed in the system are capable of monitoring the stress changes in the vicinity of mining works in deep mines. The innovative equipment can monitor both quasi-static and dynamic stress fields, using global network monitoring arrays and mobile local-scale arrays. Also, the system aims to incorporate mine production data to create an overview of the overall progress of mining works. Continuous measurements of geotechnical and geophysical data would enable early detection of high stress concentrations and unexpected microseismic activity. Determination of initial stress state of a rockmass is performed by back-computation. The stresses are first measured with CSIRO cells and stored in a database with the numerical model according to the range of measured stress states for each location. After the sufficient amount of data is collected, the next step is to fit polynomial functions. Finally, avoiding complex 3D modelling, a fast computation of the corresponding induced or initial stress state is performed from the input stress state, either initial or induced. The system enables to display time-varying curves of measured and calculated stress shifts and enhance detection of caving by analysis.
of microseismicity [13]. The concept was tested in the Garpenberg mine where the stress analysis was successfully conducted [13].

The DynaMine approach is based on matching the observed data to precalculated simulated behaviour. A three-dimensional stress state change requires six independent components. For each component, a unit response is defined and stored. For the observed ground behaviour, the corresponding linear combination of unit responses can be found using multiple linear regression. The current approach requires knowledge of the geology surrounding the sensors and elastic behaviour of the rock mass. The method may be further developed to contain excavation sequencing and to include an elastoplastic model. The latter requires knowledge of the stress path, as there are several valid plastic states.

The method of stress state change inversion using displacement measurements is explained in more detail in [14]. The inversion method was tested in Kylylahti mine in two locations. The sites were instrumented with a total of 12 multipoint borehole extensometers. The instrumentation and numerical modelling are explained in more detail in [15]. The displacement readings are read in at regular intervals, and the inversion algorithm is then run to calculate the corresponding stress changes. The results of the testing campaign are explained in more detail in [16].

The analysis method created in DynaMine can be used to create threshold values for ground control management purposes. In such approach, the acceptable limits for ground behaviour would be established along with corresponding actions if any. If the acceptable limits are exceeded a set of damage control and mitigation actions are predefined. Then during the excavation the system is continuously ran and actions are selected from the predefined list of actions. This approach is compatible with the Observational Method as described in Eurocode 7 [17].

The difference between the DIGMINE and DynaMine methodologies is that the first-mentioned solves the stress state locally around the tunnel theoretically and latter aims to estimate stress state in the larger area also solving the secondary stress state around nearby excavations. The DIGMINE per se avoids using 3D models whereas the DynaMine aims to benefit from 3D modelling. The difference can be described also so that the DIGMINE is simplified however the benefits can be also restricted and DynaMine is more complicated however with much larger benefits.

Geotechnical risk assessment guideline for underground mines has been developed at Aalto University as part of the I²Mine project [6-8, 18]. The aim was to develop a method for geotechnical risk evaluation of geotechnical hazards in deep underground mines. The methodology presented in the guideline consists of several phases (Fig. 1). The first one is the assessment of the Geotechnical Hazard Potential (GHP) that is a new form of preliminary hazard evaluation based on the combination of rock mass competency and mining method. The GHP

![Fig. 1. Geotechnical risk management workflow.](image-url)
aims to achieve preliminary information of geotechnical risk level in a mine. The result is used for justification of a formal risk assessment.

The next phase is the geotechnical risk assessment that has been proposed as a more formal stage of risk evaluation. Risk is defined as a product of the likelihood of the hazard in question and the consequence if the hazard were to be realized. GRA has been further subdivided into five steps. The first step is to outline the scope of risk assessment to know what needs to be considered. The second step is to identify hazards within the scope. While the hazard in question is strainburst, hazard identification aims at outlining all the possible ways how this hazard can realize. Of the various hazard identification tools mentioned in GRA, for a specific type of hazard, Fault Tree - Event Tree analysis is better suited for hazard identification where data is either available or will be collected for likelihood evaluation.

The next two steps of GRA are about selection between qualitative and quantitative parameters to express the likelihood and consequence. For risk assessment done in mine planning and operation stage, quantitative parameters are recommended for risk assessment. The risk assessment approach discusses how the actual likelihood and consequence of a hazard is evaluated. These are divided into 3 subtypes. The first is a deterministic way in which a direct correlation is established between measured symptom and failure. One such would be to measure roof convergence to mitigate roof fall risk. The deterministic approach however requires that the site instrumentation is extensive and is therefore an expensive exercise. The second approach is the probabilistic approach that uses spaced measurements to evaluate whether a failure will happen or not after analysing them through predetermined algorithms. Work done under the DynaMine project is one such example where measurement from extensometers was used to calculate the stress state change in a mining area [15, 16]. The third approach is derived from predictive analytics made relevant from the advent of big data [17]. The idea is to collect all possible information about a mining area without any preconceived notion of correlation between the parameters and use machine learning to identify trends within the data. This has been successfully used in the maintenance industry, which generates a vast amount of data, to do failure forecasting of components.

The likelihood of strainburst happening depends on whether the rock type in the mining area is hard and whether the stress exceeds the rock mass strength. The hardness of rock is an in situ factor and is taken into account when planning support requirements for a rock type. The stresses in the mining area are the variable that needs to be subjected to systematic evaluation. The elements involved in strainburst can therefore be divided into the stresses acting and the support system counteracting this stress. For an effective and detailed risk assessment, it is necessary that a hazard is broken down into its elemental causes so that effort is put in dealing with the root cause instead of the symptoms. For instance: de-stressing using drilling and blasting is treating the symptom when there are already signs of stresses exceeding rock strength. The hardness of rock is an in situ factor and is taken into account when planning support requirements for a rock type. The stresses in the mining area are the variable that needs to be subjected to systematic evaluation. The elements involved in strainburst can therefore be divided into the stresses acting and the support system counteracting this stress. For an effective and detailed risk assessment, it is necessary that a hazard is broken down into its elemental causes so that effort is put in dealing with the root cause instead of the symptoms. For instance: de-stressing using drilling and blasting is treating the symptom when there are already signs of stresses exceeding rock strength. Two components in a failure analysis are subsequently an element causing failure and element resisting failure. Elements that can cause strainburst are stresses that can be both mining induced and non-mining induced stresses. Elements to prevent strainburst are supports installed to counteract the stresses, which are both natural in the form of pillars/stopes etc. and artificial in the form of bolts, shotcrete, mesh, etc. These elements are then evaluated for possible failure modes, and the process is repeated until the root cause is identified. Natural supports can be overestimated for their load bearing capacity through the following failure modes: overestimation of strength from insufficient rock quality data; presence of faults and other geological structures leading to weakening of pillar strength; human error in estimation/design. Artificial supports can fail to provide the required support because of the following: poor quality support from the manufacturer; incorrect installation of the support; human error in estimation/design. Non-mining induced stresses acting on the mine can be natural seismic events. Mining-induced stresses can have failure modes as follows: unexpected stresses from blasting/seismicity; poor design of mining excavation; out of sequence mining; presence of geological structure or fractures; human error in estimation/design. The cause mentioned above can be expressed as a fault tree to arrive at the overall probability of the stresses exceeding rock strength in hard brittle rock. 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 [9]. FTA comprises three components. First is ‘Top event’ which is the primary incident that we are trying to prevent which in this case is strainburst. Second is ‘Hazards’ which are underlying causes that lead up to the incident. Third is ‘gates’ which are Boolean logic operators such as ‘and’ and ‘or’ which imply if all or either of the hazards is needed to be present to cause the accident. The probability of each primary hazard is calculated which adds up to the total likelihood
of the top event happening. Event Tree Analysis (ETA) deals with the probability of the various consequences of the top event.

When the entire fault tree is drawn, relevant data such as occurrence history may not be available to arrive at accurate probabilities of them happening. In such instances an indicative value can be arrived through consultation and follow-up measurement can be put in place to verify the number. For instance, the probability of poor quality support can be assumed at 5% based on qualitative feedback from the field. Random Quality Assurance/Quality Control tests can then be put in place to assess what the number actually is. Fig. 2 shows a fault tree diagram for strainburst risk with assumed probability values. An event tree is drawn to discuss the various events that can happen if a failure were to occur. Each possibility is evaluated for it happening or not happening. After a strainburst were to happen, some of the contributors that would decide the quantum of consequence is whether it happened in a man shift, was there a fatality or injuries, was there ore and other property loss, did it lead to a shutdown of the area. The probabilities calculations here are done mostly via consultative process, and it is advised to err on the conservative side with an overestimation of losses. This is because the main aim of risk management is to prevent an incident from happening rather than mitigating consequences once it has already occurred. Other calculation can be straightforward like in the case of a shift being manned or unmanned. If people work underground for 18 hours in 2 shifts, the probability of shift being manned is 70%. A combination of these possibilities will result in a variable tangible financial loss. Table 1 shows the event tree diagram with assumed probabilities if a strainburst were to occur in a mining area. The prefix H implies that the event will happen while NH implies that the event will not happen. In a conventional event tree analysis, the probability of each outcome is obtained by multiplying probabilities along the branches. The event tree shown in Table 1, however, combines injury/fatality and property damage/ore loss in the same event tree, but their occurrence is not necessarily dependent on each other as you can have fatality without ore loss and vice versa. Each possible consequence type has been assigned a notation in the table. From the event tree, it can be seen that there are 10 possible outcomes with a various combination of injury, fatality, property damage and ore loss which are shown in the column ‘Outcome’ with the notation in parenthesis showing the combination. The final probabilities are calculated by multiplying individual probabilities. From below example, the outcome a2 implies there is a 6% chance that following a strainburst there will be an injury and fatality including property damage without production loss in the mining
area where the incident happens. This is a product of the individual probabilities of occurrence of a manned shift, injury in manned shift, injury leading to fatality and property loss happening (H value) and production loss not happening (NH value).

Table 1. Event Tree showing various consequences arising from a strainburst.

<table>
<thead>
<tr>
<th>Strainburst (Receives probability from Fault Tree)</th>
<th>Manned Shift (M)</th>
<th>Injury (I)</th>
<th>Fatality (F)</th>
<th>Property Loss (PyL)</th>
<th>Production Loss (PnL)</th>
<th>Outcomes</th>
<th>P(Outcome)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H - 0.7</td>
<td>H - 0.6</td>
<td>H - 0.65</td>
<td>NH - 0.35</td>
<td>H - 0.4</td>
<td>a1 (M, I, F, PyL, PnL)</td>
<td>4 %</td>
<td></td>
</tr>
<tr>
<td>H - 0.6</td>
<td>H - 0.35</td>
<td></td>
<td>a2 (M, I, F)</td>
<td></td>
<td></td>
<td>6 %</td>
<td></td>
</tr>
<tr>
<td>H - 0.6</td>
<td>H - 0.5</td>
<td>H - 0.65</td>
<td>NH - 0.6</td>
<td>H - 0.4</td>
<td>a3 (M, I, F)</td>
<td>21 %</td>
<td></td>
</tr>
<tr>
<td>H - 0.4</td>
<td>H - 0.35</td>
<td>NH - 0.5</td>
<td>NH - 0.6</td>
<td>a4 (M, I, PyL, PnL)</td>
<td></td>
<td>4 %</td>
<td></td>
</tr>
<tr>
<td>NH - 0.35</td>
<td>NH - 0.5</td>
<td>NH - 0.35</td>
<td>a5 (M, I, PyL)</td>
<td></td>
<td></td>
<td>6 %</td>
<td></td>
</tr>
<tr>
<td>H - 0.4</td>
<td>NH - 0.35</td>
<td>H - 0.6</td>
<td>NH - 0.6</td>
<td>a6 (M, I)</td>
<td></td>
<td>21 %</td>
<td></td>
</tr>
<tr>
<td>NH - 0.3</td>
<td>NH - 0.35</td>
<td>H - 0.6</td>
<td>NH - 0.6</td>
<td>a7 (M, PyL, PnL)</td>
<td></td>
<td>18 %</td>
<td></td>
</tr>
<tr>
<td>NH - 0.4</td>
<td>NH - 0.35</td>
<td>H - 0.6</td>
<td>a8 (M, PyL)</td>
<td></td>
<td></td>
<td>27 %</td>
<td></td>
</tr>
<tr>
<td>NH - 0.3</td>
<td>NH - 0.35</td>
<td>H - 0.8</td>
<td>a9 (PyL, PnL)</td>
<td></td>
<td></td>
<td>14 %</td>
<td></td>
</tr>
<tr>
<td>NH - 0.2</td>
<td>NH - 0.4</td>
<td>NH - 0.6</td>
<td>a10 (PyL)</td>
<td></td>
<td></td>
<td>10 %</td>
<td></td>
</tr>
</tbody>
</table>

Event tree helps identify all the possible outcomes if an accident were to happen but does not help quantify what will be its impact on operations. Therefore it is important that due diligence is done in identifying all potential impact to the business. To communicate this better to the senior management and to get better buy-in into the process, it helps if the quantification of losses is done purely in financial terms. This helps position risk directly into the business viability and thus attracts more attention. However, calculating the true financial impact of an incident is extremely difficult as some of the intangible losses are difficult to predict especially in case of injury and fatality. While there is country specific and company specific compensation guidelines that may exist to calculate the possible financial impact of an injury/fatality, it is difficult to predict the losses caused by loss of employee morale, change in investor sentiments, negative publicity, etc. Although difficult to predict, it is important that these intangible losses are kept in mind when measuring the impact of an accident. Work done by the Mine Safety and Health Program Technical Staff of Colorado School of Mines has come up with a detailed guideline to measure possible tangible losses that can be used as a framework and it is described in [19].

A mean value for the four kinds of losses mentioned in the event tree can be used to arrive at a net financial loss. If the median cost for injury, fatality, property damage, and ore loss is € 50,000, € 500,000, € 30,000 and € 600,000 respectively, the total cost per incident if all four losses were to be realised is € 1,180,000. These financial losses can then be estimated for each of the 10 possible outcomes according to the event tree. For instance scenario a9 suggests that there is a 14 % chance of a strainburst resulting property damage and ore loss. For this mine site if there is no real-time warning system in place and with the assumed probabilities, the probabilities of a strainburst happening are 60.9 % (Table 1). Thus the combined financial loss can be estimated as the product of 60.9 % * 14 % * (€ 30,000 + € 600,000) = € 88,000.

3. Results and discussion

Measuring risk in monetary terms helps put perspective to the risk in overall business concept. A slightly modified F-N diagram can be used to represent this financial risk [10]. An F-N diagram is a logarithmic graph with
Frequency (F) of an incident along the y-axis and the number of casualties (N) on the x-axis [10]. This can be modified to include incident probability along the y-axis and financial loss along the x-axis. An intolerable and an objective line can be drawn on the F-N chart to represent the tolerable risk a business can afford. For instance, a risk above $150,000 can be considered as intolerable while $50,000 can be the objective. Any risk with a financial risk worth $150,000 is considered intolerable, and the section has to either cease mining operation until enough measures are put in place to bring it below the intolerable line. Any risk that falls between intolerable and objective indicates a risk which does not require the operations to halt, but a deadline can be set to put measures in place to bring it below the objective line. Fig. 3 shows an FN diagram with both the options of having and not having a real-time monitoring system in place. Plot points a1 – a10 show risk without a real-time monitoring system in place while Ma1 to Ma10 show risk with a real-time monitoring system in place. As can be seen from the graph, without a monitoring system, 3 scenarios fall between objective and intolerable line. However, all the plot fall below the objective line when hazard likelihood derived from a real-time monitored site is used. This can form an effective tool in seeking justification for monitoring and geotechnical risk management related expenses.

The use of real-time stress change monitoring can allow a continuous update of the probability of strainburst and the F-N diagram to know the potential financial loss. Based on the outcomes of the risk analysis, the mine management can react if the risk is above the intolerable risk level and mitigation measures can be implemented, such as ground support, the orientation of excavations, mining sequencing, and a maximum span of excavations. All actions taken must be economically feasible to satisfy the goals of the general mine project risk model.

4. Discussion and suggestion for future research

The method developed in DynaMine allows the inversion of stress state change using displacement changes. The method was benchmarked and shown to work with synthetic data. It was tested in Kylylahti mine, but the results are inconclusive, and more tests are needed. It is suggested to test the method with single instrument only in a controlled environment first to eliminate the possibility of unknown variables.

The developed method suits the need of semi-automated or fully automated risk management. It would fit well in the analysis stage of the raw data and would produce a stress state change, which could be used as input in the risk management chain. The method currently requires knowledge of geology near the sensors and elastic rock mass...
behaviour. It should be extended to support excavation sequencing and to account for rock mass damage. The method is flexible with the input data, and more input types could be programmed to allow the usage of existing mine sensor infrastructure.

5. Conclusions

Real-time monitoring can not only assist in preventing a failure but can also assist in post failure mitigations. It can help identify the possible systemic failure of adjacent areas and can therefore help in evacuating people and machinery from these areas. Using strainburst as an example risk case, the proposed Fault Tree – Event Tree methodology seems to work well. If a scenario is used where both property damage and ore loss occur, the risk can be expressed as a multiple of probability and price of consequences equating to € 88,000. Using the example data, the probability of failure drops from 60.9 % down to 12.2 % when the warning system is put into place. The associated risk level is then reduced to € 11,000. The financial consequences together with the associated risk level can be expressed visually using a modified FN graph with financial loss on x-axis and probability on the y-axis.

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