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EVALUATION OF INDUCED SEISMICITY RISK IN THE PYHÄSALMI MINE

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ABSTRACT

Recent increase of induced seismicity and high rock stresses in the Pyhäsalmi mine have proven the need for an analysis of the seismic data and prediction of hazard. Seismic events and other influencing factors are analysed in order to forecast and quantify the level of induced seismicity risk in the Pyhäsalmi mine. The expected maximum event size is found by clustering seismic data using the Quality Threshold and Single Linkage clustering algorithms, and applying the Gutenberg-Richter’s frequency-magnitude relationship. Induced seismicity risk is assessed using the Quantitative Seismic Hazard and Risk Assessment Framework. The potential for induced seismicity is calculated as a function of the maximum local seismic magnitude, rock stresses and strength, local geology, excavation geometry, and ground support capacity. The exposure to hazard is taken into account in order to quantify the level of risk. The assessment is performed on three mining levels at about 1.2 km depth, which are divided into assessment zones. Most of the assessment zones have low seismic risk and only few have an elevated potential of rockburst. The highest risk is found along the northern contact zone of ore and waste rock, adjacent to important mine infrastructure. The critical areas are identified and installation of ground support with increased dynamic capacity is recommended as a risk mitigation strategy.

KEYWORDS

Pyhäsalmi mine, high stresses, mining induced seismicity, underground mining, risk assessment

INTRODUCTION

The Pyhäsalmi mine is an underground copper, zinc and pyrite mine located in central Finland and owned by First Quantum Minerals Ltd. It is the oldest Finnish metal mine in operation and one of the oldest in Europe. Pyhäsalmi is 1440 m deep, what makes it the deepest metal mine in Europe. Over the last years mining has progressed to depths over 1000 m, what resulted in an increase in rock stresses and induced seismicity. The Pyhäsalmi mine is characterized by high horizontal stresses. The average major principal stress at the -1125 level was measured to be 65 MPa dipping at 5º towards 310°E. Results of measured and estimated in-situ stresses are presented in Table 1.

Table 1. Stress state in the Pyhäsalmi mine (Bergström, 2014).

<table>
<thead>
<tr>
<th>Level</th>
<th>σ H (MPa)</th>
<th>σ V (MPa)</th>
<th>σ h (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1135 (measured)</td>
<td>65</td>
<td>33</td>
<td>41</td>
</tr>
<tr>
<td>-1400 (estimated)</td>
<td>75</td>
<td>41</td>
<td>45</td>
</tr>
</tbody>
</table>

The quality of rock is good. Values of uniaxial compressive strength and elastic modulus for intact rock are shown in Table 2.

Table 2. Rock properties in the Pyhäsalmi mine (Bergström, 2014).

<table>
<thead>
<tr>
<th>Rock type</th>
<th>UCS (MPa)</th>
<th>E (GPa)</th>
<th>ρ (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore (massive sulfide)</td>
<td>90-120</td>
<td>90-140</td>
<td>4400</td>
</tr>
<tr>
<td>Waste rock (volcanites)</td>
<td>200-240</td>
<td>60-80</td>
<td>2700</td>
</tr>
</tbody>
</table>

Primarily, the rockmass was competent and stiff and rock was considered as prone to rockbursts. Over the last few years the ore body has detached and started slipping downwards along the ore-waste contact zone. The movement and fracturing of the orebody led to redistribution and concentration of stresses around the
orebody. The risks realised during the stoping are related to presence of orebody contact and adjacent backfilling. The increase of seismic activity in the mine is an evidence for deterioration of rockmass, hence the seismic risk has been considered as high, with large events expected to occur. The micro-seismic monitoring system installed at the mine is an important component of the investigation of rockmass conditions (Bergström et al., 2014).

The analysis of induced seismicity risk can help in estimating the seismic hazard, especially to evaluate if larger events can have a negative influence, and how they can be managed. Seismic hazard estimation is the key objective in seismic monitoring, yet there is no unique and general measure to quantify it. Seismic hazard is commonly assessed as the largest seismic event that can occur. Event size is proportional to the level of ground movement induced, which creates the potential for rockmass damage. It varies in space and time and is influenced by the location of maximum ore extraction and related stress concentration, as well as period of mine blasting. In order to predict the expected maximum size of a seismic event based on the large amount of recorded seismic events, the data has to be clustered into smaller groups. The main goal of clustering is to compress the amount of thousands seismic events into smaller groups to analyse the data efficiently. The assumption used is that a single cluster (or cluster group) represents a single seismic source. Resulting clusters (or cluster groups) can be used for the evaluation of maximum possible event that can occur within each seismic source. Hudyma (2008) illustrated a successful application of clustering algorithms in grouping of smaller clusters of seismic data in order to distinguish single seismic sources from large data sets of seismic events. He developed a Comprehensive Seismic Event Clustering methodology (CSEC) for clustering of mining induced seismic events, where two clustering algorithms were employed: the complete linkage clustering algorithm (CLINK) and the single linkage hierarchical clustering algorithm (SLINK). This study proposes a similar approach as the CSEC, but the CLINK algorithm is replaced by the Quality Threshold Clustering algorithm (QTCLUST). The main reason to use the QTCLUST is its high computational efficiency compared to hierarchical clustering methods (like CLINK or SLINK) that could not be used with large amount of data. The QTCLUST is a computationally efficient algorithm originally developed for gene clustering that groups data into cluster of high quality (Heyer et al., 1999). It can be used in grouping of seismic events to group the data into compact clusters to accelerate and improve the efficiency of analysis in terms of significant compression of data (Kaiser et al., 2005). Although it is a partitioning clustering method, it does not require specifying the number of clusters beforehand, what is the biggest advantage compared to other divisive methods (for example K-means clustering).

Seismic hazard can be evaluated as long, medium, and short-term. In comparison to earthquake seismology, comprehensive statistical seismic analysis is of limited significance for mine personnel. From this perspective, an analysis that can relate to rockmass failure mechanisms, hence coupling seismicity to mining activities, is more favourable (Hudyma & Potvin, 2010). In this study the Quantitative Seismic Hazard and Risk Assessment Framework (QSHRAF) method is used to evaluate seismic hazard and risk in the mine. This methodology was developed by the Australian Centre of Geomechanics and is applied in the Mine Seismicity Risk Assessment Program (Mikula et al., 2008). It uses the Rockburst Damage Potential (RDP) and Excavation Vulnerability Potential (EVP), which are empirical indices proposed by Heal et al. (2006) for estimation of rockburst damage potential. 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 final objective is to identify which areas require special attention in terms of elevated seismic risk and recommend measures to lower the risk, if required.

**METHODOLOGY**

This study examined mining induced seismic events recorded in the Pyhäsalmi mine during a period of 3 years, from 1 January 2011 to 27 February 2014. The number of events was equal to 103,933. The 3 year period has been selected in order to limit the amount of data for processing, mainly because of high computational demand of the clustering process, with the assumption that analysing excessive amount of events can be very slow, difficult and often redundant. Investigation of the data quality was not part of this study and the data was accepted as given. However, one abnormality was detected in the location of seismic events, so that 141 events were located above the ground surface. To avoid any further biases those events were deleted.

**Clustering of seismic events**

Clustering routine was performed using an open source programming language and environment for statistical computation – R, which has an integrated collection of statistical analysis tools and includes...
clustering algorithms applied in this study. The procedure of seismic events clustering was divided into three stages (Figure 1).

![Figure 1. Three stages of the clustering process.](image)

In the first stage, the amount of seismic monitoring data was reduced using spatial constraints. Only a definite volume of rockmass located around the production areas was taken into account, assuming it has the biggest effect on the seismic hazard level. Seismic events from within the following coordinates range were selected: for coordinate Y from 2000 to 2600, for coordinate X from 8000 to 8600 and for Z from -1500 to -900. Next, data was filtered to select only good quality data. Events with location error larger than 8 m (above 95% percentile) were rejected. Next, the outliers were excluded by applying the density based approach, which rejected single events with high isolation distance – events that did not have at least one neighbour within a sphere of a 20m radius around them were rejected.

In the second stage, the Quality Threshold Clustering algorithm (QTCLUST) was used to create compact clusters of seismic events. The QTCLUST creates non-overlapping clusters with some points remaining outside of clusters considered as outliers. The distance from a point to a group of points is calculated as the maximum length from any point from the group to the point (complete linkage using the Euclidean distance). The QTCLUST algorithm has two parametrical constraints: the minimum number of data points to be considered as a cluster (minimum cluster size), and the maximum allowable radius of a cluster (measured from the centroid). This ensures that the diameter does not exceed user-defined threshold and provides high quality and compactness of created clusters (Bednarik & Kovacs, 2012). Cluster radius of 25m and the minimum cluster size of 15 were selected in this study. The procedure of QTCLUST algorithm followed several steps:

- Create a potential cluster for random point by iteratively inserting the closest points to the already existing group.
- Repeat step one until the size of cluster is larger than the threshold.
- Save the most populated potential cluster as the first true cluster.
- Remove the already clustered points from the data and repeat the procedure with the reduced set of points.

The QT clusters created in the second stage of clustering were evaluated in order to limit the number of clusters by rejecting marginal clusters that represent minor failure of rockmass. The intensity of seismic event is expressed in local magnitude scale, which is calibrated to an approximate Richter magnitude scale. A cluster was considered as marginal if following criteria were met:

- The number of events in a cluster is low (< 20-50).
- All events are small (local magnitude < -1).
- The total amount of apparent stress is low (< 3 MPa).
- The total amount of seismic energy is low (< $1 \times 10^3$ J).

In the third stage, the single linkage hierarchical clustering algorithm (SLINK) was used to group the clusters created in the previous stage into cluster groups. The SLINK produces relatively few, elongated and chain-like clusters. At first, each data point is allocated to its own cluster. Next, the two most alike clusters are combined iteratively until there is only a single cluster. The distance between two clusters is the minimum of all distances between cluster pairs. The algorithm yields a dendrogram that represent different levels of cluster grouping, that can be cut at different heights to find the final clustering result (Jain et al., 1999).
Clusters were grouped together based on similarity of neighbouring clusters, which was evaluated using following parameters:

- parameter $b$ of the Frequency-magnitude relation (see equation 1),
- median of the S-wave to P-wave energy ratio,
- top 5 maximum magnitudes recorded (values and dates),
- top 5 apparent Stress peaks (values and dates),
- number of significant and large events,
- top 5 daily event histogram peaks (values and dates).

**Mining induced seismicity risk**

The risk of mining induced seismicity assessed using the Quantitative Seismic Hazard and Risk Assessment Framework. Assessment was performed on three mining levels 1225, 1250 and 1275, which were selected based on the amount of excavation damage and also close proximity of seismic events larger than 0 magnitude (significant events). Each level was divided into assessment zones using a square grid consisting of 20m by 20m squares indexed vertically with a capital letter from A to U and horizontally with a number from 1 to 19 (example is given for level 1225 on Figure 2). Each square in the grid (assessment zone) was assigned with four characteristics: ground support type, maximum induced compressive stress, intact rock strength (UCS) and spatial coordinates of the excavation centroid point. The support type was assigned based on the ground support map from the mine. Intact rock strength was assumed as: 75 MPa for ore, 110 MPa for ore-waste contact zone and 180 MPa for waste rock.

![Figure 2. Mining level 1225 divided into assessment zones. Colours of excavation represent installed ground support. Grey shading represents mined out stopes.](image-url)
Risk assessment started from quantification of seismic hazard by calculating the maximum possible event size for each cluster group. Frequency-Magnitude (F-M) diagram was drawn by combining all seismic events from resulting data set using the power law relation:

$$\log_{10}(N) = a - b \cdot M_L$$

where:
- \(N\) - number of events of at least magnitude \(M_L\),
- \(M_L\) - approximate Richter magnitude,
- \(a\) - constant; measure of the level of seismicity,
- \(b\) - slope of the power law relation; defines the relative number of small and large events in a certain time interval (Hudyma & Potvin, 2004).

The maximum expected magnitude for each cluster group is the x-axis intercept of the F-M diagram, assuming \(b\) equal to 1. Graphs were plotted using a range of local magnitudes. The \(a\) and \(b\) parameters (from Equation 1) for each cluster were found using linear regression (the least squares method). In the last step, each point within a single cluster group was assigned with maximum predicted magnitude, with an assumption that seismic event of predicted size can occur everywhere within a cluster group. Next, the Peak Particle Velocity (PPV) was calculated at each location under an assessment using the maximum local magnitude that is expected to occur. PPV was scaled for distance using following relation (Hudyma & Potvin, 2010):

$$PPV = 1.4 \cdot \frac{M_L}{r}$$

where:
- \(PPV\) - Peak particle velocity at the location under assessment [m/s];
- \(M_L\) - local magnitude of the largest expected event,
- \(r\) - distance from the cluster (seismic event location) to the location under assessment.

In the next step, the susceptibility of excavations for damages was evaluated using the Excavation Vulnerability Potential (EVP), which represents the increasing likelihood and severity of rockburst damage. It is calculated as follows (Hudyma & Potvin, 2010):

$$EVP = \frac{E_1 \cdot E_3}{E_2 \cdot E_4}$$

where:
- \(E_1\) - stress condition factor as a ratio of static stress to rockmass strength in the vicinity of excavation, \(E_1 = \frac{100 \cdot \sigma_{1M}}{UCS}\) [\(\sigma_{1M}\) - mining induced maximum stress at the place under assessment [MPa],
- UCS - the intact unconfined compressive strength of the rock [MPa],
- \(E_2\) - ground support capacity to withstand dynamic loading,
- \(E_3\) - excavation span, taken as a diameter of a circle drawn within mine opening [m],
- \(E_4\) - geological Structure.

Seismic hazard was evaluated only in assessment zones located outside of the orebody and on the ore-waste contact zone, because of fact that stresses inside the orebody had been redistributed and concentrated along the contact zone and around the orebody. The stress condition factor \((E_1)\) was calculated using the maximum induced stress retrieved from the numerical model and intact rock strength values described above. The values of \(E_1\) range from 5 to 59 and the \(\sigma_{1M}\) range from 5 MPa (inside the ore) to 85 MPa (outside of the ore). The ground support capacity factor \((E_2)\) was selected according to Table 3. Excavation span \((E_3)\) was calculated as a diameter of a circle drawn within excavations in assessment zones. Geological structure factor \((E_4)\) has been assigned with a value of 0.5 to assessment zones along the ore-waste contact zone as a potential failure surface promoting rockmass failure. Other zones were assigned with \(E_4\) factor equal to 1.5.
Table 3. Ground support capacity scale \( (E^2) \) for evaluation of seismic hazard (EVP).

<table>
<thead>
<tr>
<th>Support type</th>
<th>( E^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>No bolts</td>
<td>4</td>
</tr>
<tr>
<td>Mesh</td>
<td>4</td>
</tr>
<tr>
<td>Rock bolts</td>
<td>5</td>
</tr>
<tr>
<td>Cable bolts</td>
<td>5</td>
</tr>
<tr>
<td>Rock bolts and mesh</td>
<td>6</td>
</tr>
<tr>
<td>Rock bolts and cable bolts</td>
<td>10</td>
</tr>
</tbody>
</table>

The rockburst damage potential (RDP) was calculated by multiplying EVP by PPV at a specific location:

\[
RDP = EVP \cdot PPV
\] (4)

Hudyma and Potvin (2010) presented a scale of the extent of rockburst damage from R1 (no damage) to R5 (complete destruction of the support system) with an empirical chart that relates the largest predicted ground movement (PPV) to the excavation susceptibility to damage (EVP). The scale of projected damage determines the necessary dynamic capacity of ground support. If the EVP and PPV are sufficiently high and the calculated RDP predicts rockmass damage, the proper ground reinforcement that can withstand dynamic loading and large deformations is required in order to reduce the rockburst hazard and protect workers, mine infrastructure and sustain safe operation (Kaiser & Cai, 2012). By increasing the capacity of support, for example by installation of yielding support and elimination of the weakest link, the rockburst damage potential can be lowered.

The final seismic risk was calculated by taking into account exposure of personnel. Exposure is a function of the amount of time spent performing a number of tasks by mine personnel, the level of protection and the number of people involved. Areas were assigned with exposure ratings proposed by Owen (2004) in the study conducted at Australian underground hard rock mines. Exposure rating is a unitless quantity and varies from 100 to 14000. The seismic risk ratings (SRR) are qualitative: \( VL = \) Very Low, \( L = \) Low, \( M = \) Moderate, \( H = \) High, \( VH = \) Very High, \( E = \) Extreme, and depend on the type of mining activity (quantitative exposure rating) and the level of rockburst damage potential. Graphical representation of the risk matrix is demonstrated in Table 4.

Table 4. Seismic risk assessment matrix (Mikula et al., 2008).

<table>
<thead>
<tr>
<th>Excavation type or activity</th>
<th>Exposure rating</th>
<th>Seismic Risk Rating, SRR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(&lt;25)</td>
</tr>
<tr>
<td>Restricted access (no entry)</td>
<td>100</td>
<td>VL</td>
</tr>
<tr>
<td>Decline</td>
<td>1000</td>
<td>VL</td>
</tr>
<tr>
<td>Travelway - no active mining</td>
<td>1000</td>
<td>VL</td>
</tr>
<tr>
<td>Travelway - mining on the level</td>
<td>2000</td>
<td>VL</td>
</tr>
<tr>
<td>Production mucking area</td>
<td>3000</td>
<td>VL</td>
</tr>
<tr>
<td>Busy level / travelway drive / access</td>
<td>4000</td>
<td>VL</td>
</tr>
<tr>
<td>Development mining</td>
<td>7000</td>
<td>L</td>
</tr>
<tr>
<td>Production drilling</td>
<td>10000</td>
<td>M</td>
</tr>
<tr>
<td>Production charge-up</td>
<td>10000</td>
<td>M</td>
</tr>
<tr>
<td>Infrastructure areas / workshops</td>
<td>14000</td>
<td>M</td>
</tr>
</tbody>
</table>

RESULTS

Summary of the clustering process is presented in Figure 3. In the first stage 3862 seismic events were filtered out using the spatial and qualitative constraints.
In the second stage of clustering 646 QT clusters (Figure 4) were created from 100,071 seismic events. QT clusters were checked for validity using the F-M diagram drawn from the population of seismic events within clusters. Not all clusters showed good fitting of F-M diagram and both the slope and the range of linear relation was not ideal. One of the reasons was rather low magnitude range of the dataset, which resulted in faster flattening of the curve and did not allow for larger magnitude range to be approximated with linear relation. Other possibilities included poor filtering of mine blasts, erroneous parameters of seismic events, waveform corruption due to proximity of electrical noise, or even poor calibration of local magnitude.

In the third stage of clustering, 82 Cluster groups were created by combining 297 QT clusters that contained 84% of total number of seismic events (87,462 from 103,933 events) and represented 88% of the total
seismic energy (4.18 $\times$ 10$^7$ J from 4.73 $\times$ 10$^7$ J), what can be considered as a good representation of the total population of seismic events. Five most populous clusters groups are shown in Table 5.

<table>
<thead>
<tr>
<th>Cluster group</th>
<th>X (m)</th>
<th>Y (m)</th>
<th>Z (m)</th>
<th>Max. predicted M$_L$</th>
<th>No. of events</th>
<th>Seismic Energy (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S20</td>
<td>8337.8</td>
<td>2373.8</td>
<td>-1257.6</td>
<td>0.9</td>
<td>11097</td>
<td>3.60</td>
</tr>
<tr>
<td>S02</td>
<td>8268.7</td>
<td>2320.7</td>
<td>-1129.4</td>
<td>1.0</td>
<td>6564</td>
<td>1.16</td>
</tr>
<tr>
<td>S03</td>
<td>8366.2</td>
<td>2355.5</td>
<td>-1361.4</td>
<td>0.1</td>
<td>5581</td>
<td>2.30</td>
</tr>
<tr>
<td>S12</td>
<td>8379.3</td>
<td>2309.1</td>
<td>-1276.8</td>
<td>0.2</td>
<td>5579</td>
<td>1.89</td>
</tr>
<tr>
<td>S39</td>
<td>8352.9</td>
<td>2351.9</td>
<td>-1203.8</td>
<td>1.1</td>
<td>4464</td>
<td>1.16</td>
</tr>
</tbody>
</table>

Results of the seismic hazard assessment were plotted on Figure 5. The graph presents only the assessment zones with the largest rockburst damage potential (RDP). Assessment zones with no damage predicted were omitted for clarity. As can be seen on EVP vs PPV chart, four assessment zones on mining level 1225 were within the R2 rockburst damage region, which represents minor rockmass damage expected and less than 1 t of rock displaced. It is important to note that two assessment were nearly within the R2 region and only slight increase in ground motion could result in excavation damage. All other assessment areas on mining level 1225 were within the R1 region, which represents no damage or minor loose damage. The average RDP on this level was 15.8. On mining level 1250 three assessment zones were within the R3 rockburst damage region, which represents moderate expected damage and 1 to 10t rock displaced. One assessment zone was in the R2 rockburst damage region. Other zones were within the R1 zone. The average RDP on level was 15.9. Five assessment zones on mining level 1275 were within the R2 rockburst damage zone. All other zones were within the R1 region. The average RDP on this level was 16.5.

![EVP vs. PPV diagram illustrating assessment zones with the largest rockburst damage potential](modified after Mikula et al., 2008).

The results of seismic risk evaluation were plotted on Figure 6. It can be seen that 60 assessment zones on mining level 1225 had very low seismic risk rating (SRR), 8 zones had low SRR and 1 zone had moderate...
SRR. 70 zones on mining level 1250 had very low SRR, 18 zones low SRR and 3 zones moderate SRR. On mining level 1275 there were 54 zones with very low SRR, 9 zones with low SRR and 1 zone with moderate SRR. Results indicate that the majority of areas under assessment had low seismic risk and only few assessment zones were characterized by an elevated potential for rockburst. The biggest risk was found in areas located at the northern ore-waste contact zone, near the mine infrastructure such as ore passes, fresh air rescue chamber and access drive.

Figure 6. The number of assessment zones on each mining level assigned with Seismic Risk Ratings.

In areas with elevated seismic risk rating levels, the risk can be lowered either by limiting the access of personnel or through increase of ground support capacity to reduce the damage potential. As almost all assessment zones with higher risk level were located in areas that require constant access, so the latter option is preferred. In all assessment zones that have the maximum rockburst damage potential within the R2 region, rockmass damage is expected to be contained by support, so installation of surface support is sufficient in order to transfer load to individual reinforcing elements. In assessment zones on level 1250, which were within the R3 damage region, additional ground support with dynamic capacity, such as cone bolts with dynamic surface support are needed.

CONCLUSIONS

The study showed a first and successful implementation of the Quality Threshold clustering algorithm to cluster seismic events recorded in an underground mine. Due to its computational efficiency, the algorithm could handle large amount of data. Evaluation of induced seismicity risk in the Pyhäsalmi mine illustrated that the risk can be categorised as fairly low. In majority of assessment zones on three mining levels: 1225, 1250 and 1275, the level of seismic risk was found to be very low or low, and only in six assessment zones was moderate. The highest level of risk was found in areas situated close to the northern ore-waste contact zone, near important mine infrastructure, such as access ramp, shaft, ore passes and fresh air rescue chamber. Those areas require additional measures to lower seismic hazard and risk. Installation of additional ground support with dynamic capacity was recommended to prevent any severe damages in case a rockburst event will take place. The results of this study confirmed the necessity for further development and implementation of seismic risk monitoring and risk assessment as an essential component of safe mining operations in the Pyhäsalmi mine.

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