Establishment of experimental sites in three Swedish mines to monitor the in-situ performance of ground support systems associated with mining-induced seismicity

Ping Zhang, Luleå University of Technology, Sweden  
Savka Dineva, Luleå University of Technology, Sweden  
Erling Nordlund, Luleå University of Technology, Sweden  
Jouni Hansen-Haug, Lundin Mining, Sweden  
Biruk Woldemedhin, LKAB, Sweden  
Jimmy Töyrä, LKAB, Sweden  
Mirjana Bosković, LKAB, Sweden  
Anders Nyström, Boliden, Sweden  
Per-Ivar Marklund, Boliden, Sweden  
Shahram Mozaffari, Boliden, Sweden

Abstract

In order to assess the performance of ground support components and systems when subjected to seismic activity and strong ground motion, Luleå University of Technology together with three Swedish mining companies (Lundin Mining, LKAB and Boliden) started a three year research project in September 2014. The aim of the project is to develop new methods for evaluating the rock support performance in-situ that use all available information about i) the source of the seismic event (obtained from the seismic network in the mine and additional seismic sensors), ii) seismic loading (ground motion) recorded by temporary local seismic networks, and iii) the consequences of the seismic loading in terms of damage to the underground excavations and the rock support.

The sites with high potential of seismic damage were defined after the historical damaging seismic events were reviewed and the mining-induced stress disturbance was investigated with 3D numerical models. As of 31 December 2015, four sites in three different mines have been instrumented. Geophones (in depth and at surface), multi-points extensometers and instrumented bolts were installed to monitor the ground motion, the deformation of the rock mass and the elongation of the bolts. Observation boreholes were drilled to investigate the rock lithology, structures as well as fracture distribution and development. The data from locally installed geophones will be integrated with seismic data recorded by the mine-wide network. For each monitoring point, all of the instruments and observation boreholes were located at very close area within 0.5-1 m distance from each other. These results will be used to establish the relationship between the dynamic loading and the response of rock mass and rock bolts. Additionally, laser scanning is used to measure the surface deformation of the whole volume of instrumented sites with time. Two damaging seismic events occurred near the instrumented sites after the instruments were installed and the results of site investigation show that installed instruments have captured the response of the rock mass and bolts due to production blasting and seismic events.
1 Introduction

Safe and stable underground constructions are crucial to achieve optimal utilisation of mineral resources and efficient mining at great depth. The escalation of ground control problems as well as the increased occurrence of damage caused by seismic events with increasing magnitude jeopardize the safety and may lead to injuries of the personnel, damage to equipment, ore losses and unplanned operational disturbances. One of the prime concerns for deep mines is the issue related to the performance of the ground support under these conditions.

In order to assess the performance of ground support components and systems when subjected to seismic activities and strong ground motion, laboratory tests on cores, drop tests, simulated rockburst experiments and back analysis for case studies have been employed in different mines. However, none of these techniques are successful due to different limitations (Hadjigeorgiou and Potvin, 2007). The most realistic assessment of ground support systems to dynamic loads is the active monitoring of real seismic events and the corresponding damage. Unfortunately, as these events are unpredictable in time and space, the sites where the events occur are rarely adequately instrumented “a priori”. The design and selection of data for various support components would be improved if quantitative measurements were made particularly in the vicinity of large seismic sources (Ortlepp, 1984). Furthermore, many direct relationships between damage levels caused by rockbursts to the rock and ground support around an excavation and ground motion parameters have been developed (e.g. Kaiser et al., 1992; Heal et al., 2006). However the applicability of these relationships has been limited due to difficulties resulting from highly subjective assessment criteria and incomplete or questionable peak ground motion data. This limitation will only be overcome when high quality strong motion data has been collected and properly analysed (Jesenak et al., 1993). Even though seismic monitoring systems have been installed in most of the deep mines, there is still lack of systematic active monitoring and integrated information obtained from different types of geotechnical instrumentation thus resulting in difficulties to identify the seismic event mechanisms, to understand the damage process of the rock and support system, to judge the support effectiveness and to understand the interaction between the rock and the rock support during a seismic event.

Luleå University of Technology together with three Swedish mining companies (Lundin Mining, LKAB and Boliden) started a three-year research project in September 2014. The project aims at developing new methods for Evaluating the Rock Support Performance (ERSP) in-situ that use all available information about i) the source of the seismic event (obtained from the seismic network in the mine and additional seismic sensors), ii) seismic loading (ground motion) recorded by temporary local seismic networks, and iii) the consequences of the seismic loading in terms of damage to the underground excavations and the rock support, in order to find reliable relationships between the seismic event and the factors affecting the damage to the underground excavations and the rock support and in this way to reduce the number of production disturbances caused by poorly understood rock mass and rock support response, thereby decreasing the risk for personnel injury and production losses. The methodology developed for this project, the description of different types of monitoring equipment and systems, as well as the first results from the monitoring are given here.

2 Field instrumentation

2.1 Methodology

One of the main ideas in the project was to install different types of instruments in drifts/stopes where there is a high likelihood that damage due to seismic events will occur in each one of the mines: the Zinkgruvan Mine, the Kirunavaara Mine and the Garpenberg Mine, Sweden and to conduct four different measurements at each site: i) transient response of the rock at excavation surfaces and at depth as a result of seismic impingement, ii) permanent displacement changes and fracture development around excavations, iii) deformation of excavation surface, and iv) deformation development along rock bolts. Different types of monitoring data have to be integrated to establish relations between the parameters of
the seismic source/seismic waves and the performance and damage of the supported excavation (rock mass and rock support). The monitoring is complemented by numerical analyses and further forensic investigation after a seismic event has occurred.

The generic procedures followed at the experimental sites and the key instruments for field monitoring are listed below.

- **Selection of experimental sites.** In 2014, several project meetings were organized for selection of the experimental sites in the three mines. Seismologists, geologists and rock mechanics engineers were participating at these meetings to identify sites that will have high likelihood of rockburst damage during the project period 2015-2017 and beyond that time period. Preliminary numerical analyses of global models (mine scale) and analysis of past seismic data were carried out to identify areas where significant mining-related seismicity had been observed in the past and could be expected in the future. Furthermore, some criteria were defined in order to satisfy the installation requirements from a practical point of view and provide enough data within the project period. These criteria were that the sites should i) have access to services (electricity, water, compressed air, etc); ii) be far from source of mechanical noise (e.g. ventilation fans, orepass, etc); iii) be preferably recently developed and hence the instruments could capture most of effects from subsequent mining activities; and iv) be accessible as long as possible to facilitate collection of as much data as possible. After the discussions, underground visits were made to ensure that the sites met all criteria.

- **Multiple Point Borehole eXtensometers (MPBXs):** Deformation monitoring in the rock mass around an excavation at 6 discrete measurement points is carried out by using MPBXs. Therefore, the deformation development within the rock mass surrounding the excavations is evaluated before and after a seismic event.

- **Laser scanning:** Deformation of the surface of the test site is monitored by using laser scanning. After the initial scanning, the time for conducting a second scanning should be determined when the anchor of the MPBX located closest to the surface has detected deformation of more than 10 mm.

- **Instrumented bolts:** The deformation development at 6 distributed segments along the bolt is investigated by using instrumented bolts. The corresponding load development along the bolt is indirectly assessed later when the deformation is within the elastic limit of steel.

- **Borehole observation:** The holes were drilled near the other instruments and surveyed using a slim borehole camera to identify the lithology, discontinuities and changes in the rock mass (e.g. fracture development) due to mining activities and seismic events.

- **Local seismic systems:** Data from seismic sensors installed near and around the excavations of the test sites provide input for analyses of the wave field close to the excavations. This data is used to evaluate the local variations and site effects on the ground motion; and together with the data from the mine wide seismic monitoring system it is used to evaluate the seismic wave attenuation and establish the relationship between the seismic source parameters and the rock mass and rock support damage due to a seismic event.

- **Damage mapping:** Damage mapping should be conducted at the experimental sites immediately after a seismic event has occurred according to the developed forensic manual. The work should be mainly conducted by a research team with additional experts (e.g. geologists, seismologists and rock mechanical engineers) involved.

- **Numerical modelling:** Numerical models at local (e.g. drift) scale with detailed support information are built and numerical analyses will be carried out to investigate the response of the supported excavation under static loading (e.g. mining advancing) and dynamic loading (e.g. seismic event) conditions. The monitoring data is used to calibrate the numerical models.
Data recording (e.g. format, frequency), preliminary analysis, archiving procedures and maintenance schedules have been established at the beginning of this project. All data from the monitoring is also used as additional information to establish the relationship between the seismic event/seismic waves characteristics and the rock/rock support damage. Table 1 shows the summary of the experimental sites as of 31 December 2015. Figure 1 shows the schematic layout of instrumentation and instrumentation array at one of the experimental sites at the Kiirunavaara underground mine.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Summary of the experimental sites as of 31 December 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mine name</strong></td>
<td>Zinkgruvan</td>
</tr>
<tr>
<td><strong>Kiirunavaara</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Garpenberg</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Basic information</strong></td>
<td></td>
</tr>
<tr>
<td>Owner</td>
<td>Lundin Mining</td>
</tr>
<tr>
<td>Orebody at experimental site</td>
<td>Kiirunavaara</td>
</tr>
<tr>
<td>Mining method</td>
<td>Sublevel stoping (Underhand mining)</td>
</tr>
<tr>
<td></td>
<td>Sublevel caving</td>
</tr>
<tr>
<td></td>
<td>Sublevel stoping</td>
</tr>
<tr>
<td>Depth at experimental site</td>
<td>1150 m</td>
</tr>
<tr>
<td>Concern</td>
<td>Rock support for underhand mining</td>
</tr>
<tr>
<td><strong>Ground support at experimental site</strong></td>
<td>1108 m</td>
</tr>
<tr>
<td>Surface support</td>
<td>Fiber reinforced shotcrete</td>
</tr>
<tr>
<td></td>
<td>Fiber reinforced shotcrete</td>
</tr>
<tr>
<td>Reinforcement</td>
<td>NMX-Dynamic bolt</td>
</tr>
<tr>
<td></td>
<td>Fully grouted rebar</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>MPBX</td>
</tr>
<tr>
<td>Instrumented bolt</td>
<td>16 (NMX)</td>
</tr>
<tr>
<td>Laser scanning</td>
<td>5 times (planned)</td>
</tr>
<tr>
<td>Local seismic monitoring system</td>
<td>5U+3T</td>
</tr>
<tr>
<td>Observation boreholes</td>
<td>21</td>
</tr>
</tbody>
</table>

* U indicates uni-axial geophones and T indicates tri-axial geophones.
2. Instruments and site installation

To fulfil the requirements of this project, almost all of the geotechnical instruments were improved and slightly modified from their commercially available version before purchasing.

2.2.1 Multiple Point Borehole eXtensometer (MPBX)

The MPBX from YieldPoint (Canada) was chosen in this project after market survey and discussion with the three participating mines by considering the cost, service, users’ evaluation and technical flexibility. As the purpose of this project is to assess the response of the rock mass and ground support system under seismic conditions, there is high likelihood of rock fall or rock ejection near the excavation surface at the experimental sites due to possible seismic events. Therefore, the MPBX was specifically manufactured in the way that the head of the MPBX could be installed at the toe of the borehole to avoid complete loss of data due to potential rock ejection near excavation surface (collar of borehole) (YieldPoint, 2014). The lead wire was then protected by using a steel tube passing from the toe to the collar of the borehole. A trial installation was conducted in one of Boliden’s mines before formal installation of all MPBXs to investigate if there was any potential installation problem. The trial showed positive results, which proved the feasibility to use head-at-toe configuration.

MPBXs with 6 m length and 6 anchors were used in all three mines. However, different anchor locations were chosen for different mines. The anchor locations were chosen in the way that the deformation near excavation surface especially in the fractured zone can be monitored and the deformation in the rock can be compared with the deformation in the instrumented rock bolt at approximately the same depth. As the three mines used different bolt types and bolt lengths, the anchor locations for MPBX were different, see the anchor locations for the designed MPBX used at the Garpenberg mine in Figure 2 (a).

2.2.2 Instrumented bolt

A new rock bolt instrumentation strategy has been proposed and implemented by YieldPoint based on an array of sub-micron resolution displacement sensors that can measure the change in displacement or...
stretch of the bolt. The long strain-gauge based bolt instrumentation appears to provide a satisfactory performance while covering almost the entire length of the bolt based on case studies (Spearing et al., 2013). Therefore, all of the instrumented bolts used in this project were manufactured by YieldPoint.

In order to control the unit cost, the number of displacement sensors for each instrumented bolt was limited to six. The displacement sensors were arranged with three in each diametrically opposed slot (sides A and B of the rock bolt) in an end-to-end arrangement. Sensors denoted by 1, 3 and 5 are on side A and sensors 2, 4 and 6 are on side B. Two different configurations referred to as i) stacked and ii) staggered were used. For the D-bolt and the NMX-Dynamic bolt a stacked configuration was used, while a staggered configuration was used for the fully grouted rebar. A staggered configuration used for the instrumented rebar bolt at Garpenberg underground mine is shown in Figure 2 (b).

To minimize manual work, the data from the MPBXs and the instrumented bolts are recorded automatically by using d4LOGGER powered by four 1.5V batteries. The reading rate is set as 1 reading per 2h to capture the deformation change in a small time interval which is important in this project especially when a seismic event occurs.

![Figure 2](image)

Figure 2  (a) Anchor locations of the MPBX, and (b) the sensors distribution along the instrumented rebar bolt used at the Garpenberg underground mine.

### 2.2.3 Laser scanning

Field observations have shown that the deformation distribution around an excavation periphery is not uniform and localized deformation and failure has often been observed. By using 3D laser scanning, the deformation distribution of the rock surfaces of the experimental site can be obtained. However, the accuracy of measured deformation by using laser scanning is not as high as MPBX. The accuracy depends upon several factors, including the resolution and accuracy of the scanner, the accuracy of surveying targets, and the method and parameters to calculate the deformation (Feng and Röshoff, 2015).

It was therefore decided to use MPBX together with laser scanning to monitor the surface deformation of the excavation. The experimental sites were planned to be scanned at irregular periods. After the initial scanning, the time for conducting a second scanning is determined by means of the deformations measured by the MPBX, i.e., when the anchor located closest to the surface detects a deformation more than 10 mm.

### 2.2.4 Borehole camera

The first objective of using the observation holes is to identify the lithology and discontinuities at the experimental sites when they are scanned at the initial stage. The second objective is to investigate the changes in the rock mass (e.g. fracturing) as well as the development of the fractured zone with respect to extension and position due to mining advance and seismic events. Finally, the results of these observations will be used to build relationships with the monitoring results from the MPBXs and the instrumented bolts nearby. Therefore, for each monitoring point, all of the instruments and observation boreholes were located within 0.5 - 1 m distance from each other. It was decided to use a bolt rig to drill the observation holes. This means that the borehole diameter is around 26 - 38 mm which requires a small borehole camera.

The Slim Borehole Scanner (SBS) manufactured by DMT, Germany, can produce a 360° digital optical scanning of the borehole wall and was purchased with special requirement for this project. SBS has a diameter of 23 mm and can scan up to several meters long boreholes with the aid of connected pushing rods. With the DMT analysis software, the images can be used for lithological analysis, geological structural
analysis (e.g. bedding, foliation, joints, faults) and geotechnical analysis (e.g. fracture development) (DMT, 2014). The special requirement placed in the order is to improve their current depth measurement system in order to reach higher accuracy and facilitate field operation.

2.2.5 Local seismic monitoring system

The local seismic monitoring systems were installed at the same sites as the MPBXs, instrumented bolts, and observation holes. The sections in which the seismic sensors (seismic profiles) were installed (are up to ~50 cm from the other instruments. In each profile one seismic sensor is installed in the roof and two more in the walls, except at the intersections where one sensor is installed in the roof and/or one in the walls (see Figure 1 (b)).

The local seismic systems installed at the instrumentation site (not the mine wide system) consist of uni-axial and tri-axial 4.5 Hz geophones. The signal from the sensors is digitized with frequency of 6 kHz (Kiirunavaara Mine) or 12 kHz (Zinkgruvan and Garpenberg Mines). Data is collected and transferred by IMS (Institute of Mine seismology) system to the server on the surface. The timing of the seismic system is either synchronized with that of the mine wide seismic systems (Garpenberg and Kiirunavaara Mines) or Internet synchronized (Zinkgruvan Mine). The systems run mostly in triggered mode, with remote access to the data. The software for data processing is provided by IMS.

Most of the sensors (geophones) are uni-axial, installed either directly on the surface of the walls after removing the shotcrete (Zinkgruvan Mine) or in shallow boreholes, 50 - 60 cm from the surface (Garpenberg and Kiirunavaara Mines). The sensors are sensitive in a direction perpendicular to the surface of the openings. At every site/mine there are two sets of tri-axial sensors, each set consisting of one sensor installed at shallow depth and one installed in a deeper borehole 6 to 9 m. This was done to study the effect of the free surface/opening on the seismic wave characteristics (amplification, reflection, etc.). After installation and recording it was found that the clipping level of the geophones (< 10-20 cm/s) was reached for some seismic events and it was decided to decrease the gain of a few sensors at each site and increase the clipping level to be able to record larger particle velocities.

The aim of the seismic systems is to record the seismic events in the vicinity of the installed rock mechanics instruments to provide information about the dynamic response of the excavation to seismic wave loading. Furthermore, the seismic instrumentation will also provide valuable data about the seismic waveforms in close proximity to the underground openings with the variations in small distances and between the walls and the roof. Data is used: i) to study near-surface effects, the site effect on the amplitudes, frequency content, and duration of the seismic signals, ii) to study the attenuation/amplification of the seismic waves close to the underground openings, iii) to study the effect of the radiation pattern of the seismic source and the wave propagation effects, and iv) for comparison with the signals recorded by the extensometers and instrumented bolts in case of larger seismic events and rockbursts and blasting in the surrounding area. The final aim is to obtain new information that can be used for improved requirements for the rock support in rockburst prone areas.

3 Experimental sites

3.1 Zinkgruvan Mine

3.1.1 Site description

The Zinkgruvan underground mine is located approximately 200 km southwest of Stockholm in south-central Sweden. The mine has been in continuous operation since 1857, producing zinc-lead-copper-silver ore (zinc as the primary metal) by using underground mining methods. Lundin Mining purchased the mine from Rio Tinto in 2004 (Lundin Mining, 2015).

The experimental site is located at the 1150 m level in the Burkland orebody. Between -1125 and -1300 m (175 vertical metres), this orebody ranges in thickness from 5 to 45 m (average 25 m) over a strike length of
220 m. The orebody dip ranges from 55 to 85 degrees over this depth interval. The mine uses longhole primary/secondary panel stoping in the Burkland orebody. Recently underhand panel stoping has been introduced to the lower sections of the orebody. All stopes are backfilled with either paste tailings and cement or waste rock. The current primary and secondary stopes are 20 m high and 15 m wide. They are accessed from the footwall through a decline ramp with dimensions 5 m x 5 m. The ore is stratiform and occurs in a metatuffite with intercalated beds of marble, dolomite and fine grained quartzite. These beds give the ore body a distinctive stratification and significantly reduce the rock mass strength where they are abundant. The footwall rocks are generally competent and massive siliceous metatuffites (leptites). The country rock in the immediate hanging wall of the ore zone consists mainly of calc-silicate bedded metatuffite. This consists of alternating 0.5 cm to 1 cm thick layers of quartzite, quartzitic metatuffite and other metamorphosed rocks, which tend to accentuate the bedding and create ground control problems.

The experimental sites are located in the secondary stopes (S871 and S874). The support system at the experimental sites consists of 55 mm fibre reinforced shotcrete (40 kg/m³ steel fibre), 70 mm wide straps, 2.3 m long 25 mm diameter resin grouted rebars spaced on a grid of 1.2 m x 1.2 m and cable bolts with 2.0 m spacing and various lengths (7 m at sidewall, 6 m in the roof and 10-12 m at the shoulder). The details of the instrumentation at the experimental site can be seen in Table 1.

3.1.2 Monitoring results

Seven instrumented NMX-Dynamic bolts, sixteen MPBXs and eight geophones were installed at site 1 (S871) in May, 2015. Eight instrumented fully grouted rebar rock bolts, sixteen MPBXs and ten geophones were installed at site 2 (S874) in July, 2015. Until now, very small deformation has been observed in the rock mass and the instrumented bolts. However, a damaging seismic event with local (IMS) magnitude of 0.9 occurred during production blasting and produced damage along the footwall drift near the experimental sites on July 2, 2015, see Figure 3. One of MPBXs closest to the source at site 1 (S871) shows a displacement jump in Figure 4 (a) after the production blasting and the seismic event. It seems that all of the anchors (located within 4.3 m distance) were affected by the blasting and the seismic event. Comparison of ground motion in the solid rock (at 9 m depth from surface) and at the excavation surface at the experimental site 1 shows site amplification of particle velocity in the fractured zone near excavation surface (see Figure 4 (b)).

Until now, it is not clear if the damage and site amplification of particle velocity were caused by the blasting or the seismic event as the seismic event occurred during the blasting period and the detailed seismologic and rock mechanical analysis is ongoing. However, the occurred damage proves that the experimental sites are located at the right place where high possibility of rockburst could be expected during the project period.
Figure 3  (a) Location of experimental sites and damage distribution along the footwall drift, and (b) location of the blast hypocentre and the seismic event hypocentre on July 2, 2015 at Zinkgruvan mine (The red lines show the ray paths between the hypocentres and local seismic sensors.)

Figure 4  (a) Monitoring results from a MPBX, and (b) site amplification of particle velocity during the blasting and seismic event recorded at the roof surface and at 9 m depth in the roof.

3.2 Kiirunavaara Mine

3.2.1 Site description

The Kiirunavaara underground mine is located in the city of Kiruna, approximately 150 km north of the Arctic Circle in northern Sweden. The mine, owned and operated by LKAB, has been in operation since 1898 and produces iron ore. The mining method used in the mine is sublevel caving (LKAB, 2015).

The orebody is tabular and more than 4000 m long, striking almost north-south and dipping 55°-60° towards east. The width of the orebody varies from a few meters up to 150 m, but averages around 80 m. The experimental site is located at the 1108 m level and the instruments were installed along the footwall drift between y-coordinates Y32 and Y33. The main host rock type in the footwall drift is Precambrian aged trachyo-andesite (Henry and Dahner-Lindkvist, 2000), which is internally designated as syenite porphyry.
and subdivided into 5 categories with uniaxial compressive strength varying between 140 - 300 MPa (Sjöberg, 1999).

The support system which is used at the experimental site is the LKAB dynamic support designed to be used in burst prone areas. It consists of 100 mm fibre reinforced shotcrete (40 kg/m³ steel fibre), 5.5 mm diameter welded steel mesh spaced on a grid of 75 mm x 75 mm, as well as 3.05 m long 20 mm diameter D-bolt or NMX-Dynamic bolt on a grid of 1 m x 1 m. The details of the instrumentation at the experimental site can be seen in Table 1. The layout of the instrumentation and instrumentation array are shown in Figure 1.

3.2.2 Monitoring results

Seven instrumented D-bolts, seventeen MPBXs and sixteen geophones were installed at level -1108, block 34 in September, 2015. Until now, the deformation of the rock mass and the instrumented bolts is small due to the short monitoring period. However, a seismic event with a local (IMS) magnitude of 1.5 occurred on September 29, 2015 near the experimental site and created small damage on the face of the nearby excavation and sidewall at the footwall drift, see Figure 5. Plots showing the location of the seismic event, the instrumented site together with the nearby mine-wide geophones are provided in Figure 5. The MPBX at Profile 8 (Figure 1) shows a sudden displacement jump immediately after the event and all of the 6 anchors (located within 4.2 m distance) move upward with similar amplitude around 0.2 mm, see Figure 6 (a). It may be attributed to the combined effects of slip and opening of joints or fractures located between the anchors and the assembly head. The results from the instrumented D-bolt also support this interpretation as no noticeable change can be observed from the displacement sensors along the 3.05 m long D-bolt. Again, the occurred damage proves that the experimental site is located at right place where high possibility of rockburst could be expected during the project period.

Comparison of ground motion in the solid rock (at 9 m depth from surface) and near the excavation surface (at 0.5 - 0.6 m depth) shows site amplification of particle velocity in the fractured zone near excavation surface (see Figure 6 (b)). The reason why the particle velocity near the excavation surface is amplified has recently been investigated by Zhang et al. (2015) using numerical analysis. The wave frequency, fracture stiffness, fracture spacing, and number of fractures (thickness of fractured zone) are the main factors that affected the velocity amplification according to the investigation.

![Figure 5](https://example.com/figure5.png)

Figure 5  Location of the seismic event and the damage and the location of the instrumented area, together with the nearby mine-wide geophones (a) horizontal view, and (b) vertical view. The seismic event (yellow sphere), rockburst damage (black ellipses), uniaxial geophones (blue rectangles) and tri-axial geophones (red triangles) are illustrated.
Figure 6  (a) Monitoring results from the MPBX installed in the roof at Profile 8, and (b) site amplification of particle velocity during the seismic event recorded in the sidewall at Profile 5.

3.3 Garpenberg Mine

3.3.1 Site description

The Garpenberg underground mine, around 180 km northwest of Stockholm, presumably one of the oldest mines still in production, having started mining in 1200. The mine produces complex ores containing zinc, lead, silver, copper, and gold. Boliden owns and operates the Garpenberg mine since 1957.

One of the major ore bodies in the Garpenberg mine is Lappberget, where the experimental site is located. The ore body is about 300 m long along the strike and from 15 to 100 m wide. The mining method used at the site is transverse sublevel open stoping with paste backfilling. Currently transverse stoping is applied by following a primary secondary approach in Lappberget, with stopes 20 to 30 m high and width from 10 to 15 m for primary and secondary stopes respectively. The experimental site is located at the level of 728 m in the sill pillar and the instruments are installed along the footwall drift.

The support system at the experimental site consists of 30 mm fibre reinforced shotcrete (30 kg/m³ steel fibre), 5.5 mm wire diameter welded steel mesh spaced on a grid of 75 mm x 75 mm as well as 2.7 m long 25.4 mm diameter resin grouted rebar on a grid of 1.5 m x 1.5 m. 1.8 m long 22 mm diameter D-bolts are used in each mesh corner and in the mesh centre. The details of the instrumentation at the experimental site can be seen in Table 1.

3.3.2 Monitoring results

Fifteen instrumented fully grouted rebar rock bolts, twenty MPBXs and sixteen geophones were installed along the footwall drift in the sill pillar in August, 2015. The instrumented bolts were installed following the standard operational procedures and the displacement sensors for the instrumented bolts were arranged in a staggered configuration (see Figure 2). During the period of the investigation, mining (production blasting) was conducted in a stope near the experimental site on September 28 and October 10, 2015 (see Figure 7) and the ore was mined from 698 m progressively downward to 728 m below surface.

Temporal plots for one instrumented bolt and one MPBX installed in the drift roof of Profile 3 (P3 in Figure 7) are shown in Figure 8. Anchors No. 1 through 6 in Figure 8 (a) indicate the anchor positions for an individual MPBX, with Anchor No.1 closest to and Anchor No.6 farthest from the excavation. Positive values indicate that anchor and its corresponding assembly head moved away from each other while negative values mean that the two move towards each other. Unfortunately, the data-loggers could not be used...
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until September 28, 2015 and hence there were only manual readings from August 26 to September 28, 2015.

After the bolts were installed, the typical loads were in the range of 5 - 14 kN initially and then increased gradually. However, it was noted that several small jumps in the bolt load occurred immediately after production blasting. The same phenomenon was observed in the MPBXs installed around 1 m away from the instrumented bolt in the drift roof and large deformation occurred near excavation surface (Anchor 6 and Anchor 5 of the MPBXs). These events were synchronously detected by several bolts and MPBXs suggesting that they were related to definite changes in stresses and rock mass condition due to mining. Similar results have been observed by Hsiung and Ghosh (2006). General observation of the instrumented bolts and MPBX measurements and results indicated that the movements of the anchors were of two types. The first type is caused by stress re-distributions in the rock mass caused by mining and represented by a gradual increase in displacement. The second type of displacement exhibited a distinct pattern of step increase or decrease may be attributed to the combined effects of slip and opening of joints or fractures located between an anchor and the assembly head (Hsiung and Ghosh, 2006).

The displacement distributions in the rock mass and the distributions of axial strain in the bolts are plotted in Figure 9 (a) and (b), respectively. It can be seen that large amount of deformation occurred near the excavation surface within 1.3 m distance. The load (proportional to the strain) along the bolt is developed along the central section of the bolt at 0.8 – 2.1 m distance from the surface with the maximum load located at 1.1 m away from the surface. So far, the maximum strain along the bolt is still lower than the elastic limit (2500 microstrains) of the bolt during the monitoring period.

Figure 7  Layout of instrumented profiles (marked as P1, P2, ..., P7) and stopes blasted before and after the installation at the experimental site at the Garpenberg underground mine.
Figure 8  (a) Displacement development with time from a MPBX, and (b) strain development with time from an instrumented bolt in the roof on Profile 3 at the Garpenberg underground mine.

Figure 9  (a) Displacement change and (b) strain change over the monitoring period for the MPBX and instrumented bolt in roof at Profile 3 at the Garpenberg underground mine.

4 Conclusion
The ERSP project aims at developing new methods for evaluating the rock support performance in-situ that use all available information about i) the source of the seismic event (obtained from the local seismic network in the mine) and ii) the consequences of the seismic loading in terms of damage to the underground excavations and the rock support. Until now, four sites in three different mines have been instrumented.

Two damaging seismic events have occurred near the experimental sites at the Zinkgruvan Mine and the Kiirunavaara Mine after the instruments were installed. Even though they did not produce large disturbance and damage to the rock mass and rock support at the experimental sites, the results prove that the location selection of the experimental sites is right. The effects due to mining/production blasting have been monitored by the installed instruments which manifests the installation of the instruments is successful. The accumulative damage effect in rock and rock support has been captured by the instruments, which gives extremely important information for us to evaluate the loading and deformation...
history and further the excavation vulnerability potential before a seismic event occurs. The project is ongoing and more promising results are expected and could be obtained in this project.

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