Local seismic systems for study of the effect of seismic waves on rock mass and ground support in Swedish underground mines (Zinkgruven, Garpenberg, Kiruna)

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Abstract

Three local seismic systems were installed by August 2015 in deep underground mines in Sweden – Zinkgruven Mine (Lundin Mining AB), Garpenberg Mine (Boliden AB), and Kirunavaara Mine (LKAB) as part of a project for developing new methods for Evaluating the Rock Support Performance (ERSP, Vinnova). The areas were chosen within the most probable volumes where large rockbursts can be expected. The local systems were installed at mine levels between 730 and 1150 m in different mines. The horizontal extend of each instrumented areas is between 70 and 100 m. The seismic system in each mine is a combination of uniaxial and three-axial 4.5 Hz geophones installed on the surface, in shallow (~0.5 m) and deeper (6-9 m) boreholes in profiles across drifts. These profiles are in close proximity to profiles with extensometers, instrumented bolts, and observation holes. The seismic systems are manufactured and installed by the Institute of Mine Seismology (IMS). The aim of the seismic systems is to record the seismic events that occur in the vicinity of the instrumented areas and provide valuable data about the variability of seismic waveforms around the underground openings and changes when seismic waves approach them. Data is used to study: 1) the attenuation/decrease of the maximum ground velocity (PPV) with the distance, especially at small distances; 2) site effects, including maximum amplitudes, predominant frequency, and duration of the seismic signals, 3) the attenuation/amplification of the seismic waves approaching the underground opening. The final aim is to obtain new information that can be used for improved requirements for the rock support design in rockburst prone areas.

The installation of the seismic systems started in May 2015 (Zinkgruven Mine) and was completed by August 2015. They run mostly in triggered mode with initial automatic arrival time picking and source parameter calculation and subsequent manual processing of seismic event of interest. More than 200,000 seismic events with magnitude from -4.5 to 2.0 were recorded by December 2015. At present only a small portion of all data was processed manually and the procedures for processing of the events were developed on this subset. The first results from the monitoring showed that there are differences in the amplitudes and shape of the seismic signals recorded by the sensors installed in deeper borehole (behind the most blast-damaged zone (6 – 9 m)) and close to the surface (0.5 m) or on the surface of the openings. There are also differences between the waveforms recorded on the walls and the roof along the same profiles or on nearby profiles. Data from the investigated rockbursts showed maximum velocity recorded from a seismic events at close distances with magnitude larger than 0.5 in the order of 10 cm/s with clipping levels 10 – 20 cm/s.

1 Introduction

Rockbursts are major safety issue in deep underground mines around the world. They are also a problem for deep underground mines in Sweden. To reduce the hazard due to rockbursting one of the most important factors is the adequate rock support. The optimal rock support should be designed according to the specific conditions in the mines and real ground motions generated by the induced seismic events in
The first results presented in this paper are based on the data obtained from three local seismic systems installed as part of the ERSP project, combined with data from the existing permanent seismic systems in the participating mines. They include: 1) attenuation/decrease of maximum velocity of the ground motion (PPV) with the distance; 2) local variations of the ground motion caused by local site effects (differences in the maximum amplitude, duration, and predominant frequency); 3) attenuation/amplification of the seismic waves approaching the underground opening.

2 Local seismic monitoring systems

Local seismic systems, consisting of 16-18 sensors were installed in three underground mines in Sweden – Zinkgruvan Mine (Lundin Mining AB), Garpenberg Mine (Boliden AB), and Kiirunavaara Mine (LKAB) in May to August 2015. The sites were chosen within the volumes where larger seismic events and rockbursts were expected to occur based on previous seismic events or expected production development. The mine level of the areas where the local systems were installed varied between ~1150 m (Zinkgruvan), 1100 m (Kiirunavaara), and 730 m (Garpenberg) (Table 1). Geophones with natural frequency 4.5 Hz were installed within comparatively small horizontal span (70 to 100 m) on vertical profiles crossing the underground openings. The local seismic system for Zinkgruvan and Garpenberg Mine are shown on Fig. 1. The layout of the seismic system in Kiirunavaara (Kiruna) mine is presented in Zhang et al. (2016).

Table 1 Summary of the seismic local systems as of 31 December 2015

<table>
<thead>
<tr>
<th>Mine name</th>
<th>Zinkgruvan</th>
<th>Kiirunavaara</th>
<th>Garpenberg</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basic information</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Owner</td>
<td>Lundin Mining</td>
<td>LKAB</td>
<td>Boliden AB</td>
</tr>
<tr>
<td>Orebody at experimental site</td>
<td>Burkland</td>
<td>Kiirunavaara</td>
<td>Lappberget</td>
</tr>
<tr>
<td>Depth at experimental site</td>
<td>1150 m</td>
<td>1108 m</td>
<td>728 m</td>
</tr>
<tr>
<td>Local seismic monitoring system*</td>
<td>12U+6T</td>
<td>12U+4T</td>
<td>12U+4T</td>
</tr>
</tbody>
</table>

* U indicates uni-axial geophones and T indicates tri-axial geophones.

Most of the sensors are uniaxial. They were installed on the surface of the openings (Zinkgruvan) or in shallow holes (50-60 cm from the opening behind the most damaged rock mass) (Garpenberg, Kiruna), with their axes oriented perpendicular to the opening. There are also sets of triaxial sensors installed in pairs – one in deeper boreholes (6 to 9 m) and the other in shallow boreholes (50-60 cm) (Fig. 1). The aim of the surface/shallow sensors was to provide input for analyses of the wave field close to the excavations and to study the local variations and site effects of the seismic waves. The aim of the deep/shallow pairs of sensors was to study the transfer function (modification of the seismic waves when they approach the opening/free surface). Data from all sensors was used also to study the attenuation/decrease of the seismic waves (peak particle velocity – PPV) with the distance, combined with the data from the seismic sensors of
the existing permanent seismic systems in the mines and to establish relationships between the seismic source parameters and the rock mass and rock support damage due to rockbursts.
Figure 1  Schematic diagram of seismic local system in Garpenberg Mine (top) and Zinkgruvan (bottom).
The signal from the seismic 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) equipment to the server on the surface. Timing of the seismic system is either synchronized with the timing of the permanent seismic systems (Garpenberg and Kiirunavaara Mines) or it is 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.

After the installation and recording for a few months was found that the clipping level of the geophones (~10-20 cm/s) was reached for some seismic events. The gain of a few sensors at each site will be decreased in order to increase the clipping level and to be able to record larger ground motion velocities.

The geomechanical instruments for the project, which include Multiple Point Borehole extensometer (MPBX) and Instrumented bolts (from YieldPoint, Canada) were installed in proximity (distance up to ~50 cm) to the seismic systems. Observation holes for 360° digital optical scanning by Slim Borehole Scanner (SBS) (DMT) were also drilled. Laser scanning technique is used to monitor the closure of the excavation. For a detailed description of all instrumentation see Zhang et al. (2016).

3 Seismic data and processing

During the period from May/August 2015 until December 2015 each one of the seismic systems recorded large amount of very small to larger seismic events (magnitudes from −5.0 to 2.2(??)). The seismic systems run mostly in triggered mode with initial automatic arrival time picking and source parameter calculation. The manual verification of the results showed that the accuracy of the automatic arrival time picking was not enough for precise localization of the hypocenters and it was decided to process manually a subset of events. The criteria for choosing events were the number of sensors that recorded the event (> 15) and if any sensor recorded an event with PPV (Peak Particle Velocity) > 5 mm/s. (The clipping level was ~10-20 cm/s.)

To get reliable seismic source parameters manually picked arrival times from the local seismic systems were combined (merged) with the data from the existing permanent seismic systems and processed together. IMS Trace software was used for the initial routine processing and calculation of source location and dynamic source parameters. As the number of sensors and the geometry of the permanent systems are very different in each mine, and time synchronization was available only in Kiruna and Garpenberg mines, there were some modifications in the processing approach for each mine. Merging of the data was straightforward for Kiruna Mine, which has the largest number of permanent sensors (~230) and the best sensor coverage. The hypocenter locations and estimated size of the events in this case did not differ substantially between the permanent seismic system and the merged data. For Garpenberg Mine the comparison of the results for the hypocenter locations from the permanent system and the merged data showed very large differences depending on the azimuthal coverage (Erguncu Güçlü, 2016). In some cases the differences in the hypocenter locations between the two systems was in the order of 200 m with the large difference in the hypocentral depth. In this case special investigation was carried out to find the best solution. The results from the merged dataset were chosen as final for Kiruna and Garpenberg mines. For Zinkgruvan Mine only data from the local system was used for calculation of all source parameters as the permanent seismic system is very sparse and the closest seismic sensors are far from the local sensors and there is no time synchronization between the local and permanent seismic systems.

The first results presented here are based on data from events recorded in the three participating mine until the of December 2015.

4 PPV decrease with the distance

The peak particle velocity (PPV) is an important parameter which is used in the underground support. The PPV values obtained by the permanent seismic systems in the three participating mines in the best case
scenario are at hypocentral distance around 100 m. Data for the near field, close to the seismic sources are very sparse. The installed local seismic system provided unique opportunity to obtain data very close to the hypocenters of the seismic sources, in some cases at 10 m, and to fill in the gap in the near field. The largest PPV that were recorded on unclipped records were in the order of <10 cm/s for seismic events with magnitude > 0.5 and distances up to 100 m. For the seismic events with magnitude between 0.0 and 0.5 the PPV was up to 25 mm/s. (The magnitude used in this study is the local IMS magnitude, calculated from the seismic energy and potency.)

The decrease in the PPV was studied by IMS for Kiruna Mine (de Tout et al., 2012) and two empirical relationships were derived from the data from the permanent seismic system. These relationships were tested on the data from both, permanent and local seismic systems for all three mines (Fig. 2).

![Graphs showing PPV decrease for Kiruna, Garpenberg, and Zinkgruvan Mines.](image)

Figure 2  Examples of the PPV (vertical component) decrease for Kiruna, Garpenberg, and Zinkgruvan Mines.

The results showed that relationship derived for the potency as a parameter in overall fits better the data from all mines. The empirical relationships using energy as a parameter are underestimating the real data. Even though the relationships were derived for data from Kiruna Mine they fit quite well the data from Garpenberg and to some extent from Zinkgruvan. As only data from the local seismic system in Zinkgruvan were used, the conclusion is based only on data at close distances. These first results give indication that the PPV decrease at short distances up to 100 m is very fast compared to the decrease at larger distances. This means that data at larger distances cannot be extrapolated to obtain the PPV decrease at short distance. It has to be noted that the empirical relationship in de Tout et al. (2012) is extended at short distances using theoretical considerations not real data.

The work will continue with more data and with a goal to find empirical relationship for the PPV for each one of the mines as a function of the potency/seismic moment, magnitude, and seismic energy.
5 Local variations of seismic spectra

One of the aims of the project is to define the variability of the seismic waveforms and their parameters as amplitudes, frequency content, and resonant effects recorded in close distances around the underground opening, e.g. possible site effects. The initial stage of the analysis included only visual inspection for substantial differences in the frequency content and possible resonances. We looked in which cases (hypocentral distances, magnitudes, and azimuth of the rays from the source to the sensors) there are effects that are noticeable visually.

Examples of stacked S-wave spectra for seismic events recorded in Zinkgruvan and Kiruna Mines are shown on Fig. 3.

a)
The results from the three datasets from different mines showed that the spectra in Zinkgruvan Mine have more variability than in the other two mines. In some cases the differences in the spectral level is 7-9 times. The sensors with larger amplitudes are not always the same and the frequency at which larger amplitudes are observed varied. There is also indication that even though the differences in the spectral shape and level in the other two mines (Kiruna and Garpenberg) are not so large, there are still visible and more variability is observed when the azimuthal paths differ more (Fig. 3b, left) than when they are closer (Fig. 3b, right). In Zinkgruvan Mine the variability in the spectral shape is observed even in cases of comparatively close raypaths. The most plausible explanation for the differences in the behaviour of the spectra in Zinkrivan Mine compared to Garpenberg and Kiruna Mines, could be that the sensors in the first one are installed directly on the surface of the opening after removing the shotcrete while the sensors in the other two mines are installed in shallow holes (50-60 cm) from the opening. More sensors will be installed in different conditions close to each other to verify this plausible conclusion.

The work will continue with statistics on the differences of the spectral level and dominant frequencies as a function of the magnitude of the seismic events, the distance and the azimuth. The difference in the waveforms recorded in the time domain will be studied also. An example of different records from an event recorded in Zinkgruvan Mine at almost the same distances is shown on Fig. 4.
Figure 4  Example of waveforms from seismic event with M = -3.4 recorded in Zlnkgruvan Mine at distances from 34 to 43 m.

6 Transfer function

At every site/mine there are at least two sets of triaxial sensors installed, each set consisting of one shallow sensor and one in a deeper borehole 6 to 9 m from the opening. These pairs of sensors are used for study of the effect of the free surface/opening on the seismic wave characteristics (amplification, reflection, etc.). To obtain the transfer function the S-wave spectra on different components were calculated and the ratio of the spectra between the surface/shallow and deep sensor were calculated.

Examples of the original records and the spectral ratios for each component (one vertical and two horizontal) are shown on Fig. 5.
Figure 5  The original records from both surface and deep sensors (left) and the S-wave spectral ratios component by component (right) (X and Y are horizontal components and Z is vertical component). The pairs of sensors are on the roof of the opening (top) and on the wall on the same vertical cross section. Data is from an event with $M = -0.2$ recorded at distance 78 - 80 m in Kiruna Mine. The amplitude scale is different for different records and is shown in the left upper corner of each record (MaxAmp).

The first results obtained for the spectral ratios are very consistent. They show almost no difference in the spectral level of the records from the shallow and deep sensors for up to 100 Hz. Between 100 and $\sim 1000$ Hz the spectral level of the records from the surface sensors is up to 10 times larger than that of the deeper sensors and above 1000 Hz this level is a few times smaller. The further work will try to find a physical
explanation of the observed phenomenon. More work will be done on the statistical representation of the results obtained from larger number of records and in different conditions in different mines.

7 Conclusions

The first results obtained from the local seismic systems installed in three different Swedish mines – Zinkgruvan, Garpenberg, and Kiruna showed differences in the seismic events recorded at close distances up to 100-200 m in a few different aspects: variation of the waveforms recorded almost at the same distances but in different positions (roof or wall) and at different azimuths from the seismic sources. The corresponding spectra also differed but mostly for the sensors in Zinkgruvan Mine, which were installed on the surface of the opening, and less in Kiruna and Garpenberg Mines with shallow sensors installed at 50-60 cm deep holes. An interesting result obtained so far is the amplification/de-amplification of the seismic waves coming towards the opening, different for three frequency bands: up to 100 Hz – no amplification, 100 to ~1000 Hz amplification of almost 10 times, and above 1000 Hz de-amplification a few times. The results for the PPV decrease show that the new data fill in the gap for very small hypocentral distances and can give valuable information about the changes in this parameter for these distances.

The work will continue with more processed data and statistical representations of different kind of results to find the dependence on the magnitude of the seismic events, possibly the mechanism of the seismic source, the distance and the azimuth of the raypaths. It has to be mentioned that in many cases (for larger seismic events) the data recorded by the local systems are within the source radius (so-called ‘near field’). In these cases the usual representation of the seismic source as a point source is not acceptable and the work has to be done with more complex representation of the seismic source.

The results of this study and within the ESRP project can give valuable empirical data for improvement of the understanding of the seismic wave field near the seismic sources in the mines and subsequent improvement of the principles of the rock support design in the mines.

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