Harnessing microseismic monitoring

Dr Dave Collins and Dr Zara Hosseini of ESG Solutions explain how microseismic monitoring can be used to generate valuable information and mitigate economic and safety risks during cave mining

As fewer orebodies become easy to access, operators are shifting deeper underground and towards new bulk-mining methods for more cost-effective production. The economics of bulk-mining methods such as caving are much more attractive, especially in mines with large volumes of lower-grade ore.

Caving operations have opened up new potential for underground bulk mining, but also introduce challenges for mining engineers.

Paramount to these challenges is the lack of access to the caving front. Microseismic monitoring provides indirect visualisation of the cave front when no visual inspection would normally be possible. The far-field nature of microseismic system coverage overcomes the lack of physical access to the cave front to install ground support or instrumentation, improving cave assessment and management.

High-resolution microseismic monitoring has proven to be one of the most effective ways to understand cave growth and track the progression of the cave front over time.

ESG's Paladin acquisition system allows the continuous monitoring of seismicity induced during mining operations. Consisting of a group of seismic sensors distributed throughout a mine in a strategic array of underground and surface locations, a typical microseismic system aims to locate and evaluate mine-induced seismicity accurately.

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WHY MONITOR?

Microseismic monitoring, used in mines for more than 20 years, presents a critical tool to improve production and mitigate risk in underground operations. Seismicity is common in mining operations, as the rock shifts in order to redistribute stress in the rock mass. Typically, induced seismicity is measured on a micro-scale at levels equivalent to very small earthquakes measuring -3Mw to +1Mw in magnitude. However, on occasion, microseismic systems may be combined with strong ground motion sensors on the surface to record larger-magnitude seismicity (up to +4Mw).

Identifying the location and size of these seismic 'events' and evaluating seismicity temporally and spatially as it relates to mining operations serves as an essential tool to quantify and understand stress-induced rock-mass behaviour.

Since microseismic monitoring reveals continuous information about what is happening behind walls and in areas not accessible to mine workers, it can operate as an early-warning system for potential hazards caused by changing rock conditions. If a system is installed early in a mine's life, there is an opportunity to collect background-level data on seismicity in the mine so that, over time, operators begin to recognise what is normal seismicity and what may be a cause for concern.

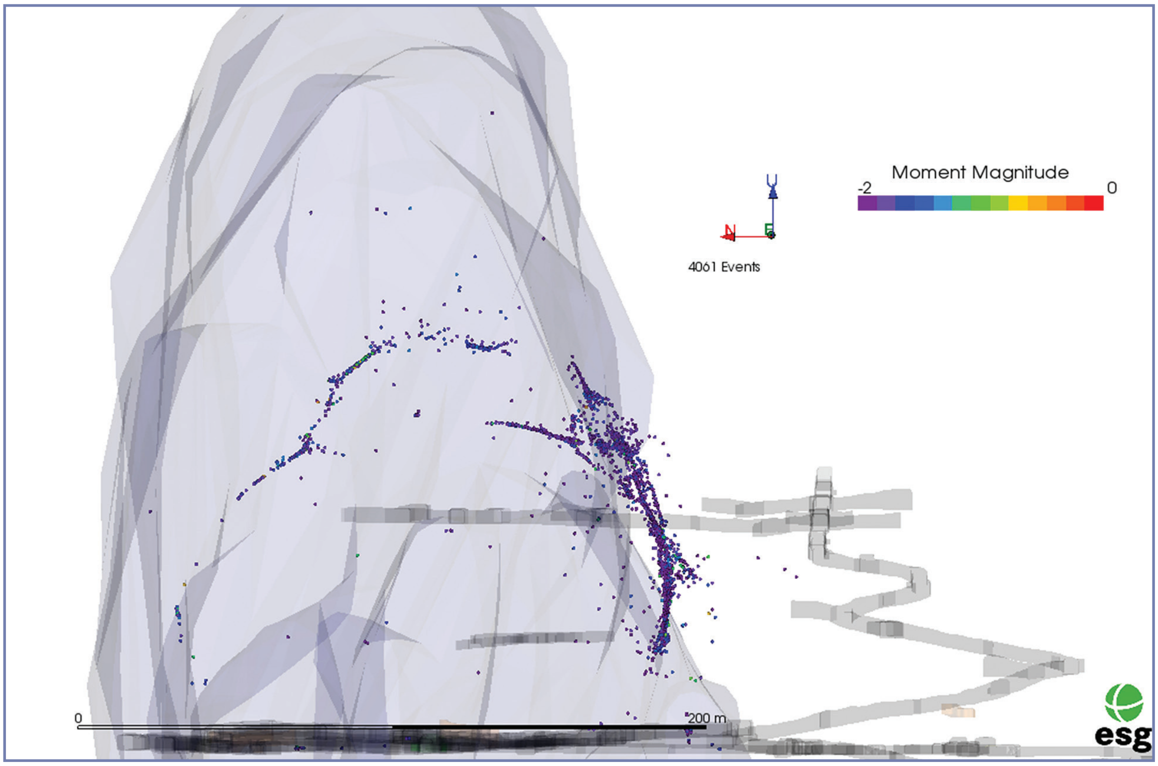

Figure 1: Example of microseismic events tracking the caving front for two production sequences. Notice the distinct images of the caving front as it propagates upwards

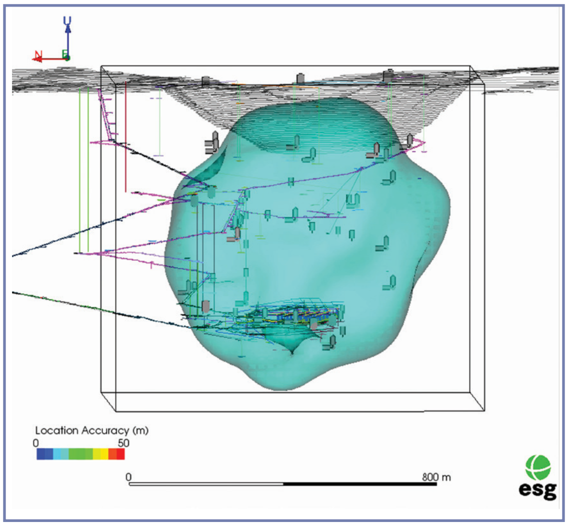

Figure 2: Location errorspace results are plotted as a light-blue 3-D isosurface (16m location error) superimposed on the mine workings. The sensor locations are shown as grey cylinders.

In particular, this information may be used to deploy workers in less hazardous regions of a mine, adjust ground support and calibrate or confirm numerical models used for mine design and sequencing to manage seismicity more effectively and improve mine safety.

In caving operations, microseismic monitoring can be used to identify the fractures taking place in the seismogenic zone – the region of rock mass directly ahead of the caving front. Figure 1 provides an example of microseismic events that track the progression of the caving front over two production sequences. Evidence of interaction or activation of previously unknown geological structures may allow operators to slow down production or remove people and equipment from nearby headings.

A reduction in observed seismicity may indicate a build-up of stress in the rock mass, which, if it fails suddenly, could harm the mine and pose a threat to worker safety. Seismic information helps operators to better understand what is taking place in the rock mass, providing an opportunity to:

- correct the production plan;
- adjust the mining rate and strategy; or
- implement safety measures.

Seismicity observed during caving can also be used to help evaluate proposed rock-failure mechanisms. If the leading failure mechanism identified by seismic monitoring does not agree with models to predict the cave behaviour, mining operations may be exposed to significant risk in later stages. Seismic monitoring allows operators to calibrate and adjust models, and implement corrective actions to avoid conditions that could close a portion of a mine.

DESIGN AND INSTALLATION

The first and most important step to implementing a seismic system for caving operations is to design a 3-D sensor array that effectively covers the cave zone as it progresses.

ESG performs a detailed array design to determine the best position of each sensor in the array, as well as identifying which types of sensors should provide the best performance based on the estimated rock-mass properties. An array design offers an estimate of the expected event location accuracy, and the minimum detectable magnitude sensitivity in and around the cave zone.

Various sensors, including accelerometers and geophones in uniaxial and triaxial configuration, can be used:

- **Triaxial sensors:** provide high accuracy when calculating source parameters (magnitude, energy, source radius and apparent stress) and source mechanism analysis as ground motion at each sensor location is recorded in three directions.
- **Uniaxial sensors:** are more cost-effective and can be deployed in greater density, contributing to higher source location accuracy and magnitude detectability.
- **Surface-based 4.5Hz strong ground**

- **motion sensors:** these may also be installed to capture larger-magnitude seismicity related to mining operations.
- **Accelerometers:** these are more sensitive to higher frequencies and identify, record and locate smaller-magnitude events more effectviely.
- **Geophones:** these are preferred in some environments to capture a clean, high-quality signal at lower frequencies.

> “High-quality seismic data also presents opportunities to gain further understanding of rock-mass behaviour”

For hard-rock mines, ESG prefers to install a combination of accelerometers and geophones to cover a wider magnitude range of seismic events.

In general, an effective array design aims to distribute sensors throughout as much of the volume of interest as possible. An example of a mine-wide microseismic array utilising a mix of uniaxial accelerometers and triaxial geophones to monitor block-caving operations is provided in Figure 2.

To provide a high-resolution microseismic system for a block-caving operation, it is possible to install a number of seismic sensors in deep boreholes from the surface, as well as sensors in shorter boreholes from underground tunnels. Together, these installations help to build an optimal 3-D array.

ESG has considerable experience in deep borehole installation for mining, geotechnical, oil and gas applications; current installations are deployed as deep as 2.2km. Borehole geophone arrays may be installed permanently or temporarily – for a few weeks up to several years. Some seismic sensors can also be installed inside the upcoming cave zone to track microseismicity more accurately in the early stages of caving. These sensors will eventually be lost as the cave progresses but will provide valuable information on early progression of the cave. It is important that any seismic sensor be robust and able to perform in harsh underground conditions. ESG's sensors are rated at 241.3bar to a depth of 2.5km.

Sensors are connected to 32-bit Paladin digital seismic recorders that receive and digitise seismic data relating to individual microseismic events before transmitting the data to surface stations for analysis.

Underground and surface-based units are synchronised using GPS to ensure that all recorded events are located accurately in space and time. Each Paladin unit is a web-enabled device (for remote access/calibration) and can provide continuous and/or trigger-based data acquisition.

ENSURING ACCURACY

To assess the progress of the cave, it is critical that microseismic event location and interpretation be as accurate as possible. Events are located using first arrivals of P- and S-waves. Hodogram analysis determines the direction to each source, and a velocity model is applied to determine a preliminary event location.

Inaccuracy in event location can often be traced to the use of an inadequate velocity model. A single velocity model can be used to represent a homogeneous isotropic material, in which all seismic energy would propagate outwards from the source with a 3-D spherical wave front. Such a model has been shown to work well in many hard- and soft-rock mines. However, in many cases, a layered velocity model is used to account for the different geological bedding layers.

In caving operations, the existence of a massive void in the centre of the sensor array results in signal attenuation and longer travel paths from seismic sources to the surrounding sensors. To ensure velocity models are the best possible representation of actual conditions in the subsurface, ESG has developed a 3-D ray-tracing algorithm to take into account this void and its changing volume with time. This 3-D algorithm can also consider any significant heterogeneous geology with different properties and wave velocities in and around the mining zone (see box).

While there is no doubt that accurate tracking of seismicity during cave mining provides valuable information to operators, well-distributed, high-quality seismic data also presents opportunities to gain further understanding of rock-mass behaviour via advanced seismic analysis.

Full waveform seismic data can be analysed further to provide detailed information on source parameters (magnitude, energy, source radius and apparent stress) and source mechanisms. Event clustering and source radii values can lead to conclusions about fracture coalescence and macrofailure processes. Trends in certain source parameters can be used as indicators of the relative level of stress at the seismic event.

Source mechanism studies can offer important insight into the failure processes in the back of the cave, and have the ability to differentiate between shear sliding, tensile opening and crack closure.

Microseismic methods offer a unique opportunity to monitor a 3-D volume of rock and visualise the zones of a rock mass experiencing rock failure in real time. For caving applications, this information helps to shed light on how a rock mass is behaving, and gives operators valuable information that can be used to help mitigate economic and safety risks during mining.

Seismic wavefront propagation through a heterogeneous rock mass

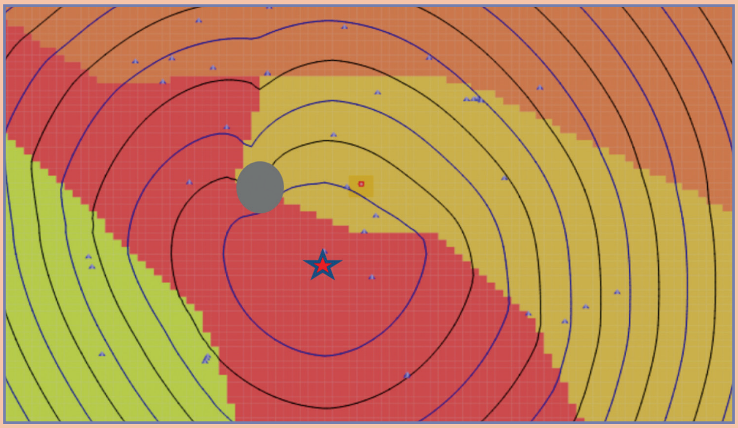

Figure 3: cross-section showing isolines of equal travel time from a seismic event location (star symbol) outwards through the rockmass. The isolines are seen to be significantly affected by the cave zone (grey filled circle)

An example of the seismic wavefront propagation through a heterogeneous rock mass with a cave zone is shown in Figure 3.

In this case, the model has been adapted to account for the effect of the cave zone, as well as differences in geological units throughout the mine. These geological units exhibited elastic properties that varied by up to 10% from each other.

The isolines are observed to be significantly affected by the cave zone (grey circle), as well as the different geological domains with irregular boundaries.

Applying this algorithm and modifying the cave geometry in the velocity model as it progresses significantly improves the location accuracy of seismic events. For this calibration blast example, the algorithm was found to reduce the location error by about 50%.

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