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Tremors in cave mining

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ABSTRACT

Monitoring cave propagation is a key operational objective in cave mining. Common approaches are based on borehole observations and seismic monitoring data constrained by a height of draw assessment. Conventional seismic monitoring data characterises the stress-driven processes (episodes of brittle failure on the external boundary of the cave yield zone). Sometimes there is an over-reliance on numerical models and/or an under-utilisation of available seismic data where assumptions about the rock mass may lead to an oversimplification of the problem and inevitably bias results towards an adopted mental picture of the caving process. A new type of data is observed at caving mines (tremors), which is likely related to gravity-driven processes – deformation near the internal boundary of the cave yield zone or sudden movement of rocks within the cave. Routine seismic data processing for mines has evolved in recent years to include pick-less methods in the overall workflow. As a result, the processing of tremors has recently become a routine practice, which provides extra information to help understand the state of the cave. The aim of the paper is to present a new type of seismic monitoring data, discuss the challenges regards to processing and consider potential applications for mass mining operations.

1 INTRODUCTION

Different types of low-frequency seismic events and their uses are described in seismological literature. Examples include signals often associated with volcanic eruptions. Volcanic tremors typically have dominant frequencies of 1-9 Hz and represent movement of magma (Yukutake et al. 2017). Studies of slow deformation phenomena collectively referred to as “slow earthquakes” have implications for forecasting future activity in tectonically active regions like subduction zones (Ide & Nomura, 2022). These are distinguishable by frequency content and may be referred to as slow-slip events (SSEs), low-frequency events (LFEs), very-low-frequency earthquakes (VLFEs) or tectonic tremors. Quite recently, it was shown that induced earthquakes with hybrid-frequency waveforms (EHWs) recorded during unconventional oil and gas production (Yu et al. 2021) could represent a transition from aseismic to seismic slip. The characteristics of EHWs are very similar to the tremors observed in cave mining and discussed in this paper.

Mining in general induces a variety of deformation types with only a small percentage recorded as seismic. A relevant example can be found in Hilbert et al. (2014) where the authors present an analysis of the seismic signals from Bingham Canyon Mine landslides recorded by the Global Seismograph Network. The available low frequency recordings (1-5 Hz) allowed the authors to make quantitative assessments of bulk landslide parameters. Slow deformation seismic events in cave mining are in a way, analogous to small-scale landslides but the characterisation and use of this data is hindered by the imposed limitations of in-mine seismic sensors.

Controlling cave and, by extension, yield zone growth is pivotal to block cave operations. The analysis of seismic data is arguably the most useful tool in understanding the rock mass response as it contains 4D information about sudden strain change or movement of rocks whereas other methods are either indirect measurements strongly affected by input parameters (e.g., travel-time tomography, numerical modelling) or geometrically constrained to boreholes (e.g., down-hole observations, smart markers). Conventional seismic monitoring in mines is typically focused on signals with clear arrivals of P- and S-waves. These are generally related to the stress-driven processes (sudden slip along weaknesses, shear failure within the rock mass, rapid stress fracturing on the perimeter of excavations, episodes of brittle failure on the external boundary of the cave yield zone, etc.). The amount, direction and type of sudden deformation at the source are described by seismic moment or seismic potency tensors, which can be evaluated from recorded seismic signals. The moment/potency tensors inverted from recorded seismic data make it possible illuminate the rock mass deformation as illustrated for example, by Birch & Meyer (2019).

A new type of data is observed at caving mines, which is likely related to gravity-driven processes – deformation near the internal boundary of the cave yield zone or sudden movement of rocks within the cave. Conventional processing methods based on the identification of corresponding pairs of P- and S-waves are not suitable for these. The source description based on seismic moment or potency tensor may also not be applicable, if the process involves a unidirectional rock mass motion (mass advection). In such cases, the seismic radiation needs to be described by a single force mechanism (Malovichko, 2022).

This paper aims to demonstrate how the range of available seismic data can be expanded to include "slow deformation" events in cave mining. The result is a significantly improved interpretation of caving performance.

2 WHAT ARE TREMORS?

Typical seismic events recorded by in-mine seismic sensor arrays have well-defined features such as dominant frequencies in the range 100 Hz to 1 kHz, high signal-to-noise ratios (>10), clear and separable body-wave arrivals. Such signals allow for an accurate estimate of the hypocentre and parameters that define the nature of the source using well-established pick-based methods (Figure 1).

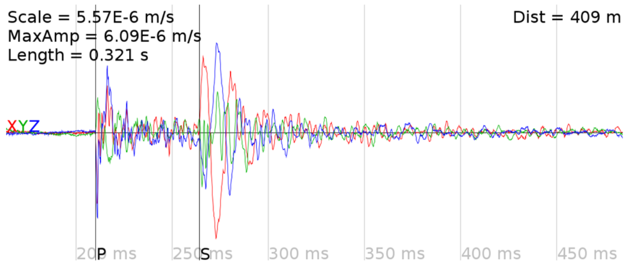

Figure 1 Three-component waveform of a typical micro-seismic event recorded by 14 Hz geophone grouted in solid rock.

A caving-induced tremor is best described as slow, gravity-driven deformation. This may be induced through a reduction in the confinement stress. An example of the waveform data is shown in Figure 2 where we see an almost monochromatic low-frequency signal with a noticeably lower signal-to-noise ratio than in Figure 1.

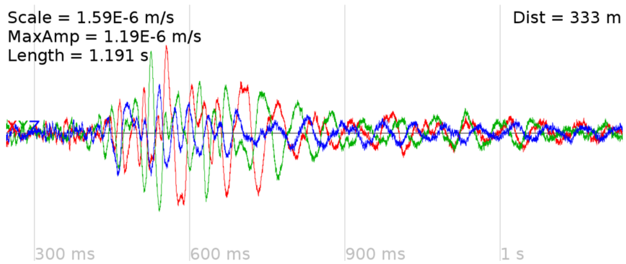

Figure 2 Typical three-component waveform of a small caving-induced tremor event recorded by 14 Hz geophone grouted in solid rock.

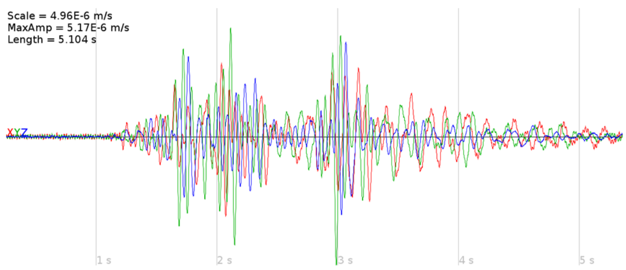

Figure 3 Example of a very large tremor recorded by an in-mine sensor array of geophones grouted in solid rock.

Tremors can also be extremely large to the point where they are felt on surface at large distances from the mine. An example of such an event is shown in Figure 3. The signal has a very long duration (>3 seconds) and the amplitudes at these low frequencies were large enough for the event to be felt in a nearby town.

The differences between a typical shear type event and a tremor are best highlighted by their respective spectrograms. In Figure 4 we see most of the energy from a typical shear type event (Figure 1) is in the range 10 Hz to 100 Hz within a short period of time (< 0.1 sec), whereas in Figure 5 the energy is spread over ~0.7 sec in a relatively narrow frequency range, below 20 Hz.

Based on our interpretation of observations to date, we therefore propose that tremor waveforms can be modelled assuming the source is equivalent to a series of rock falls in the cave back or side. A stable cave back (arch) may be disturbed by sub-vertical, gravity-driven movement (or fall) of a key rock fragment in the cave back or side, which may trigger similar movement (or falls) of other fragments until a new stable configuration of the cave is reached.

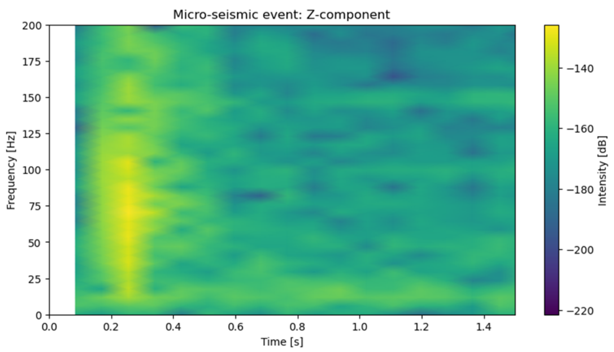

Figure 4 Spectrogram of the waveform of a typical micro-seismic event displayed in Figure 1.

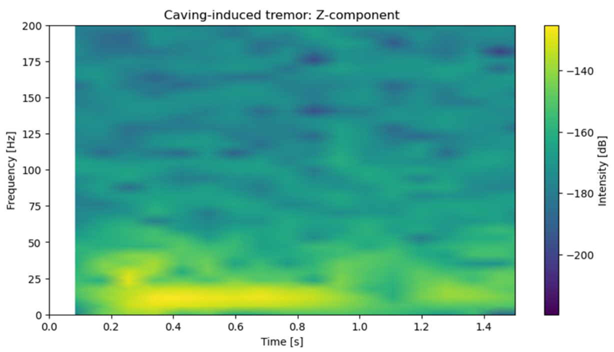

Figure 5 Spectrogram of the waveform of a caving-induced tremor displayed in Figure 2.

3 HYPOCENTRE ESTIMATION OF TREMORS

It becomes clear when inspecting waveform data of tremors, for example Figure 2, why pick-based methods are ineffective at deriving basic source parameters. The body wave arrivals cannot be clearly separated and the dominant low-frequency content leads to large pick uncertainties, prohibiting consistent arrival time estimates across multiple triggers of the same event.

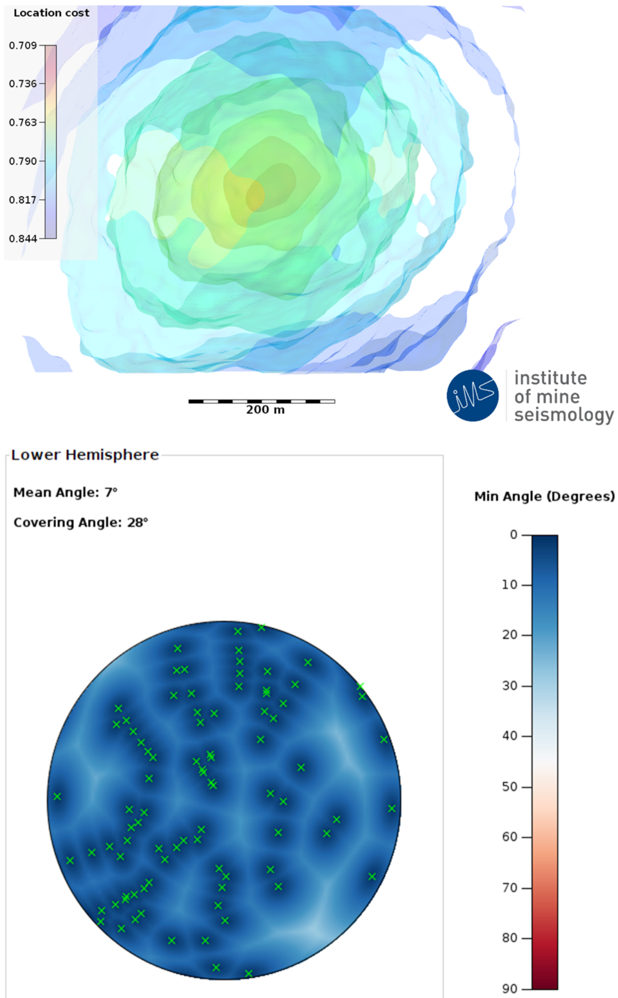

Figure 6 Top - Cost-function result gridded in a 500 m x 500 m x 500 m volume around the best hypocentre estimate. Bottom - Corresponding focal sphere sensor coverage.

Gal et al. (2021) developed an automatic processing routine that uses in part the cross-correlation of characteristic functions derived from seismic waveforms. Reverse migration of the resulting lag times onto a spatial grid is used (Dale et al., 2017) to calculate a mean cross-correlation value. For tremors we assume lag times correspond to correlated S-waves for unique pairs of sensors (S_1S_2). The decision to use only one cross-pair stems from the expectation that the largest contribution to the radiated seismic energy is shear deformation at the source.

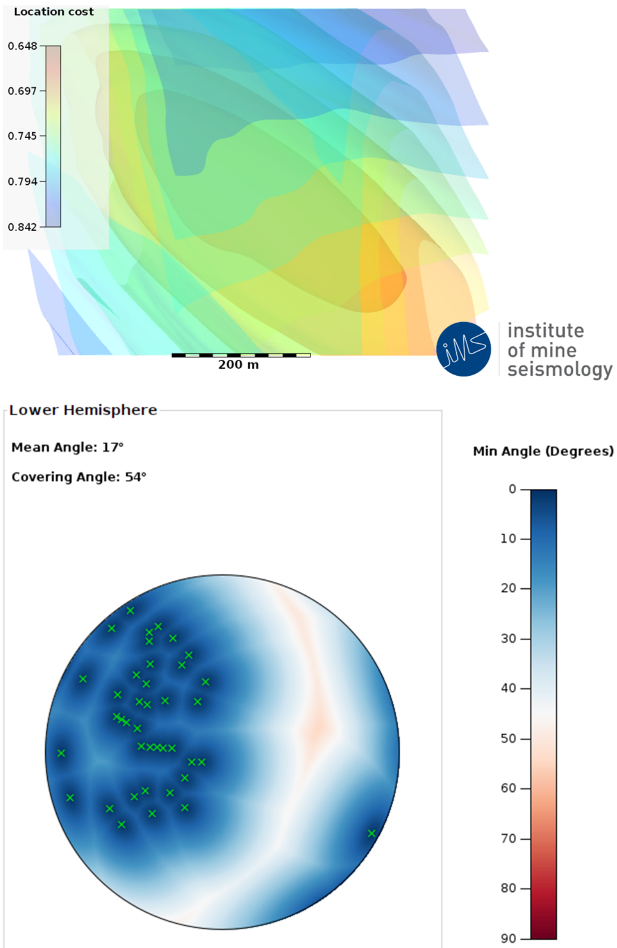

Figure 7 Top - Cost-function result gridded in a 500 m x 500 m x 500 m volume around the best hypocentre estimate. Bottom - Corresponding focal sphere sensor coverage.

A consequence of this approach to locating tremor sources is a strong reliance on focal sphere sensor coverage. Tremors that trigger a small number of sensors or originate outside the sensor array will not have reliable hypocentre estimates using this method. Figure 6 shows an example where a high level of sensor coverage produces a spatially constrained distribution of cost-function minima. Figure 7 shows how inadequate coverage produces poorly constrained minima leading to smearing over a large volume. Another weakness of the cross-correlation method is that it only works if the sensor array is time-synchronised.

4 A POSSIBLE METHOD TO ESTIMATE SOURCE SIZE

Tremors are currently parameterised only in terms of origin time and hypocentre location. In order to be included in the calibration of numerical models some estimate of the source dimension is required. Conventional source parameter estimation methods cannot be applied without clear and separable body-wave arrivals. In addition, conventional processing is based on potency or moment tensor representation of the source (typically a slip-type mechanism). If the radiation is described by a single force, then the standard source parameters (scalar moment or potency) no longer hold meaning. The low-frequency (< 30 Hz) seismic radiation from each rockfall can therefore be described by a sub-vertical single force. By modelling the waveforms of a known tremor source it is possible to empirically relate some measurable quantity to a geometrical parameter of the source to facilitate interpretation of the date.

The time history of the single force includes two phases of the process; (1) an upward rebound of the surrounding rock mass during detachment, and (2) downward impact imposed on the mobilised material within the cave. The phases are parameterised by the mass of the rock fragment/block and travelled distance (free fall height). This source model represents a particular case of the general mass advection source model presented by Takei & Kumazawa, (1994). Scenarios of tremor sources may be constructed using the following procedure/assumptions about the source:

- For hypocentre location, randomly draw tremors from a volume encompassing some percentage of recorded tremors at a mine.

- Randomly select a number of rockfall impacts per event by drawing from a uniform distribution.
- Randomly select the mass of an individual rock fall from a uniform distribution of the fragmentation.
- Randomly select the height of free fall from a uniform distribution constrained by knowledge of the maximum air gap.

Figure 8 shows an example of modelled waveform data from tremor source.

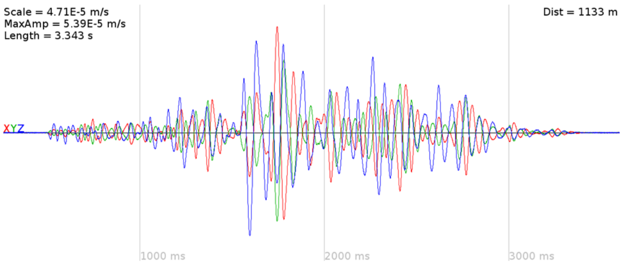

Figure 8 A synthesised waveform emitted by a tremor source with a 2 second duration involving 32 impacts, a total mass of 173,500 tonnes and a fall height of 1.2 m.

Input parameters of the modelled sources therefore include total mass, height of free fall or sum of the product of mass and travelled distance for individual episodes of fall/movement. Observables inferred from the waveform data may include some intensity measure based on cumulative absolute displacement or peak ground velocity, or typical source parameters such as seismic energy or potency (although the latter does not hold a meaningful interpretation in mass advection source models).

The resulting empirical relationship can be used to calculate the total volume of mobilised mass for a comparison with production data or numerical modelling results. However, the relationship will more than likely depend on the elastic properties of the rock mass and need to be re-calibrated.

5 IMPLICATIONS FOR CAVE MONITORING

Tremors have been observed in nature and characterised as a type of slow deformation event with a variety of different source types and mechanisms. We have discussed similar signals recorded in a mining environment, the associated mechanism and provided a description of the tools required to extract information that can be used to interpret the rock mass response.

Monitoring tremors in mines has the potential to provide information about large volumes of yielding rock (block caves). Temporal and spatial changes related to production may be better constrained in cases where the rock mass is less seismic. For a better understanding of the hazards related to cave mining, tremors can be used in approximations of the air gap, cave yield zone and timing of surface breakthrough. Numerical models today struggle to differentiate between seismic and aseismic deformation, including an estimate for the deformation represented tremors helps to bridge this gap.

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