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Seismic Resonance Modes for Mine Roof Stability Monitoring

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SUMMARY

This work aims at the detection of instabilities in underground mine roadway roof, with the goal of predicting and preventing roof failure and collapse.

Openings in the rock have their own resonances, due to the propagation of seismic waves in the rock around the opening. If the surrounding rock is damaged or fractured, this would result in the resonant frequencies decreasing. An experiment was set up in an underground mine to detect these resonances and see how they change in the process of rock degradation leading up to collapse.

Accelerometers were grouted into a mine roadway roof, along with displacement and stress sensors. Waveforms from mining-induced microseismic events were recorded. The spectra of the coda of these events were used to search for resonances. Strong resonance modes were indeed seen, which were stable over time. The resonance frequencies did decrease in the days prior to roof collapse, in parallel with measured stress changes. At the time when significant movement was detected in the roof rocks, the resonance modes changed completely, probably due to delamination of the rock causing seismic decoupling. This means that resonance modes could be used for roof stability monitoring.

Key words: resonance, mining seismology, mine roof stability

INTRODUCTION

Roadway roof fall in underground mines can cause fatalities and, in Australian coalmines for example, typically results in millions of dollars of lost production every year. The ability to monitor roadway roof conditions and predict roof fall would therefore be valuable.

There are various mechanisms of roof collapse. The work described in this paper is addressed to coal mines, where the rock shows near-horizontal sedimentary layering. In a sedimentary geological environment, high stresses cause the rock layers in the roof to delaminate, buckle, and finally to fracture and fail. These processes will affect the propagation of seismic waves passing through the rock. Changes in stress affect seismic velocity, newly-created fractures change both velocity and attenuation, and resonance modes in the rock layers will be changed by delamination. The aim of the work described here is to detect seismic resonance modes in the mine roof, and to determine whether changes in these modes associated with the processes leading up to roof collapse could be used as part of a warning system.

Similar ideas have been used at a smaller scale to detect loose slabs in a mine roof. Standard practice is to strike the roof with an iron bar, and listen to the response – a "drummy" sound indicates that the rock is loose. This idea has been used by Hanson (1985) who used the difference in amplitudes at two different frequencies as a diagnostic for a loose slab of rock. The rate of decay of vibrational amplitude has also been used to characterise areas of potential failure in coal mines (Altounyan & Minney 2000). A system that measures roof resonance remotely using laser Doppler vibrometry has been tested (Swanson 2002).

Here we instrumented the roof, of a roadway that we knew would fail as the mining face passed, with seismic, strain and displacement sensors, to see whether resonance modes were present in the roof, and whether changes could be detected preceding roof collapse. Resonances are indeed present, and their frequencies shift in parallel with stress changes. Finally, immediately prior to roof failure, the resonance structure changes completely, presumably because of seismic decoupling caused by delamination.

RESONANCE FREQUENCIES

An infinite rockmass will have a continuous spectrum, i.e. there will be no resonance peaks. However, resonances are often observed in practice on sensors around mine openings. One possible explanation is that the mine opening itself is resonating: there are various modes of wave propagation around the surface of the opening, including Franz waves, propagating at the velocity of the surrounding rock, Rayleigh and Stoneley waves propagating in the rock, and "whispering gallery" modes caused by internal reflection within the opening (Korneev 2009).

The vibrational response of a rock structure can be modelled as a distributed system of mass and stiffness elements (see for example Siggins & Enever 1979). The system of differential equations describing the vibrations can be written in matrix form as

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{R}(t)$$

where **M**, **C**, and **K** are matrices of mass, damping, and stiffness respectively, while **R**(t) is a time-varying applied load. **u** is the vector of displacements, with the single and double dots representing time differentiation yielding velocity and acceleration. Writing **u** as

$$\mathbf{u} = \phi e^{i\omega t}$$

and neglecting the damping term results in the eigenvalue problem

$$\mathbf{K}\boldsymbol{\phi} = \omega^2 \mathbf{M}\boldsymbol{\phi}$$

The solutions consist of eigenvectors φ associated with discrete eigenvalues (frequencies) ω.

If there is a change in the rockmass, such that the stiffness is reduced, then the eigenvalue problem becomes

$$(\mathbf{K} - \Delta\mathbf{K})\boldsymbol{\psi} = \beta^2 \mathbf{M}\boldsymbol{\psi}$$

with $\Delta\mathbf{K}$ being the change in stiffness, and β the new frequencies. It can be shown (Siggins & Enever 1979) that

$$\beta_i^2 = \omega_i^2 - \boldsymbol{\phi}^T \Delta\mathbf{K}\boldsymbol{\phi}$$

The new frequencies are smaller than the original ones. This means that the introduction of fractures, with low stiffness, into the rock will result in a decrease in the resonance frequencies.

METHOD AND RESULTS

A gateroad roof in a coal mine in New South Wales was instrumented with an array of accelerometers grouted into holes drilled into the roof, along with strain and displacement instruments (Shen et al. 2008). The gateroads lie on either side of the panel being mined, and so are guaranteed to experience roof failure as the mining face passes. Data was collected over a period starting when the mining face was hundreds of metres away, until after it had passed the monitored location, and the roof had collapsed.

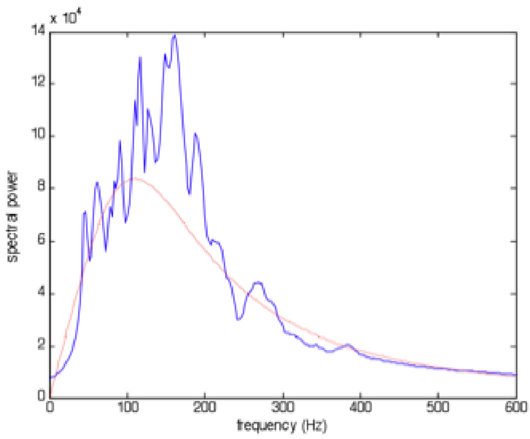

Figure 1. Spectrum of the coda of a microseismic waveform (blue). The red curve show a best-fit Brune earthquake spectrum.

The seismic system was set to trigger on microseismic events, in order to detect and locate fracturing caused by the mining. A short waveform snippet was recorded for each triggered event. In order to search for resonances in the data, I used a window of data preceding the arrival of the P wave in each snippet, along with the coda – that energy present later than the P and S wave arrivals.

A typical ground velocity spectrum is shown in Figure 1. The broad background shape is consistent with a Brune-model earthquake spectrum, but has distinct sharp peaks superimposed. Some of these peaks are obviously multiples of 50Hz power signals, but others appear to be part of the rock response. A Brune spectrum with amplitude and corner frequency chosen to minimise the least-squares difference is shown as a red curve.

In order to examine the consistency of these possible resonance peaks, the spectra of seismic events in a moving time window were averaged to produce a smoothed time-frequency plot, shown in Figure 1. The colour image shows the energy recorded on a single sensor as a function of time on the x-axis, and frequency on the y-axis. Red indicates high amplitudes, and blue means low amplitudes. The white sections are where the instruments were not functioning due to power outages. A period of about ten days is shown.

Superimposed on the time-frequency plot are displacement measurements from nearby sensors in blue, stress measurements in red, and the total number of detected seismic events in black, all as a function of time. The dramatic increase in displacement (blue) towards the end indicates the point where the roof starts to collapse. The increase in the number of detected seismic events shows that roof damage is taking place.

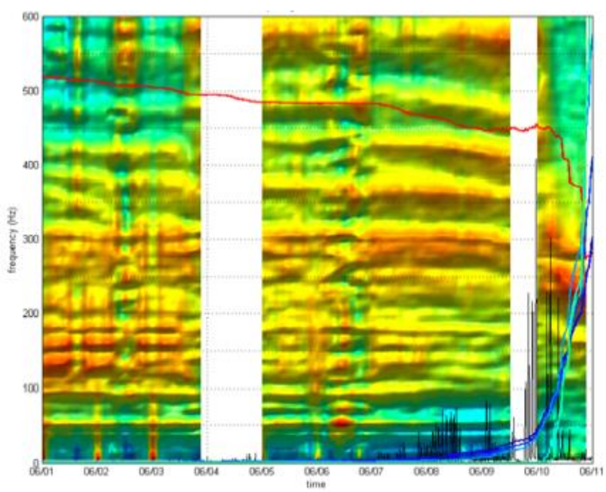

Figure 2. Seismic resonances. The colour image shows amplitude of vibration from red (high) to blue (low) as a function of time (horizontal axis) and frequency (vertical axis). Several resonances are apparent, whose frequencies decrease at late times. Nearby measurements of stress (red) and displacement (blue) are overlaid, along with microseismic event rates (black).

Many of the resonance peaks are indeed consistent across much of the image. The 50Hz power peak is particularly clear, along with associated harmonics. Many other, slightly broader, peaks are also visible. Interestingly, the frequencies of these peaks decrease in the days immediately prior to roof collapse, roughly in parallel with the stress changes shown in red. At the point where the displacement sensors show significant roof movement, the resonance structure changes completely, probably indicating a delamination, and seismic decoupling of the rock containing the accelerometer from its surroundings.

These changes in resonance frequency corresponding to changes in rock stress, and changes in the number and spacing of resonance modes with delamination of rock units, could potentially be used to warn of impending rock fall.

A quick-and-dirty numerical model was constructed using the finite-difference code suea2df from Seismic Un*x. A rectangular, 6m x 3m roadway was embedded in rock with typical sandstone velocities, and a point source 100m distant was used to excite the roadway. An example snapshot is shown in Figure 3. The expected scattered P and S waves are shown receding away from the roadway. But the roadway is also acting as a resonating source – smaller amplitude waves with strong periodicity can be seen around the roadway.

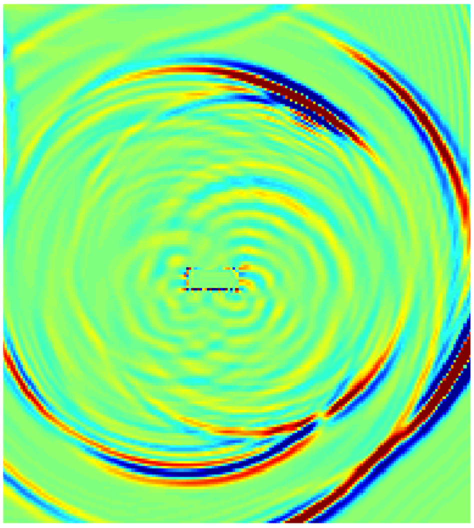

Figure 3. Resonances of an underground roadway. Snapshot of numerical wavefields interacting with a 6m x 3m opening in the rock. The scattered waves are clearly visible as high-amplitude P and S waves. The rectangular opening can be seen to emit periodic waves of lower amplitude for a substantial time after the scattered waves.

CONCLUSIONS

Theoretical considerations show that a rock-mass system exhibiting resonances will show decreases in the resonance frequencies, when failures – regions with low stiffness -- are introduced into the rock mass. An experiment was conducted to try to detect these resonances.

Accelerometers were grouted into the roof of a mine roadway that was destined to collapse. Displacement and stress sensors were also installed. Waveforms from mining-induced microseismic events were captured by the system. The high-amplitude P and S direct arrivals were stripped from these events, leaving the coda waves. These were used to produce spectra of the roadway roof.

Strong resonance modes were seen, with frequencies that were consistent over the course of the experiment (periods of days). Interestingly, the frequencies decreased in the days prior to roof failure, as the stress instruments registered a decrease in stress. As the roof started to move significantly, the resonance patterns changed completely, most likely indicating that the roof had delaminated and was seismically decoupled from the surrounding rock.

The phenomenon of resonance of an opening in the rock being induced by a nearby seismic event can be reproduced by numerical modelling.

The observed resonances, and changes in their frequencies and number of modes, could be used to develop a hazard-monitoring system for roof stability.

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