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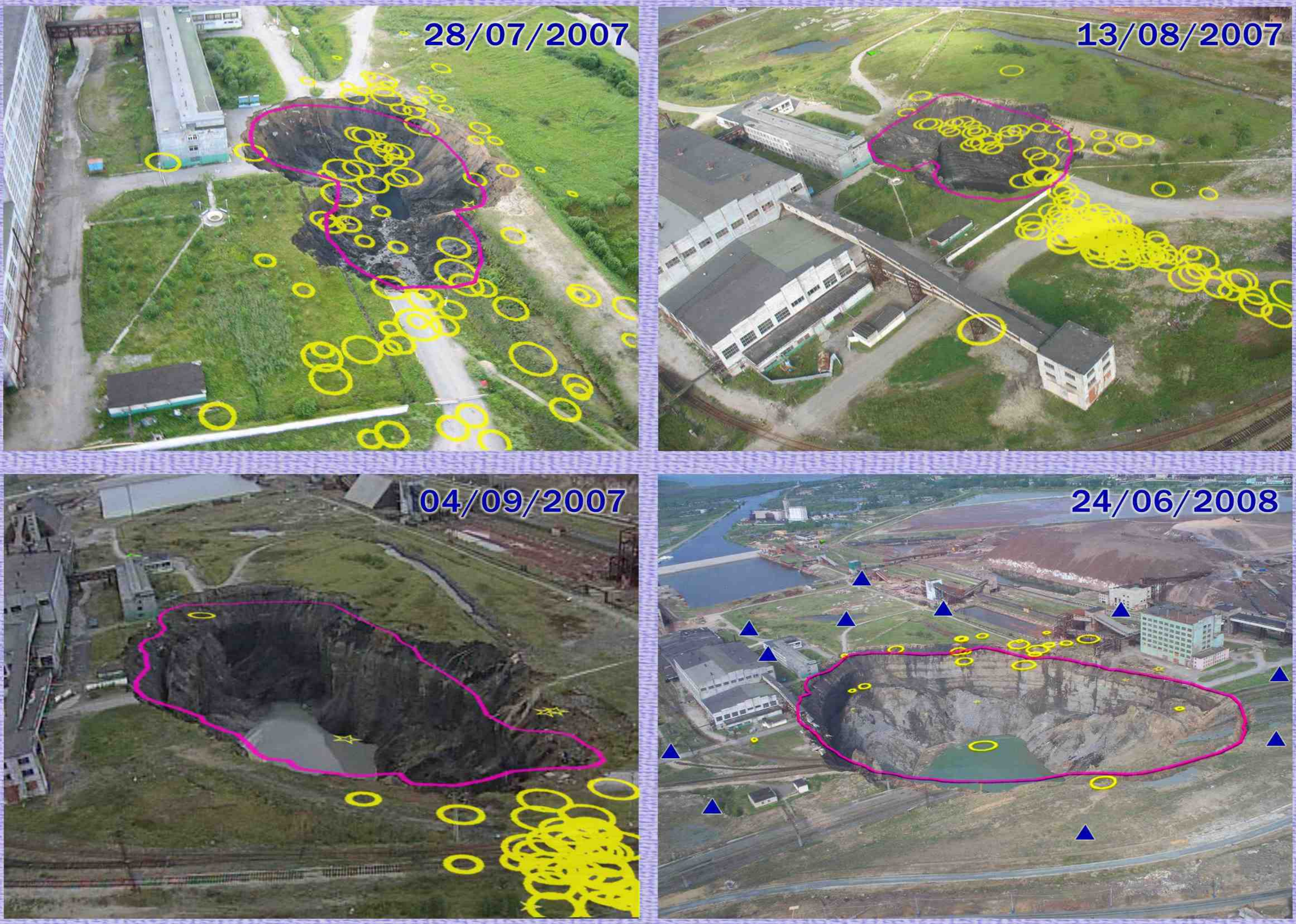
ROCKBURSTS AND SEISMICITY IN MINES



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HIGH ACCURACY MEASUREMENTS OF SEISMIC VELOCITY VARIATION IN MINES

R.A. Lynch, G. Olivier and M.T. Green
Institute of Mine Seismology, Stellenbosch, Republic of South Africa

To better understand the rockmass response to mining – specifically changes in stress and fracture density – it is desirable to accurately measure changes in the body wave velocities. Ideally this should be achieved over distances of at least 300 m with resolution of 0.01% or better. Two approaches to this problem have been discussed here: the use of controlled seismic sources and ambient noise.

Three types of controlled seismic sources have been discussed: piezoelectric, rotating mass and pneumatic. The piezoelectric source produces hourly estimates of relative seismic velocity variation with an indicated resolution of around 1.3 × 10^{-3} using a standard borehole geophone over a range of 80 m in a highly attenuating rock mass. The rotating eccentric mass source produces a very strong signal amenable to spectral analysis techniques, but requires a small phased array to separate the P- and S-waves, making this source less practical. The pneumatic source generates clear, repeatable signals with a signal-to-noise ratio equivalent to an hourly resolution of 5 × 10^{-5}, and so is the best of the sources tested, although long-term reliability is unknown.

The ambient noise technique has been explored with a 3D numerical model of Beaconsfield mine (Australia). Recordings of noise in an underground mine was used as seismic sources in a few places in the mines, and synthetic seismograms generated. This synthetic data was analysed using the ambient noise technique and shown to yield estimates of seismic velocity variations to a resolution of 10^{-4}. Theoretically, a stable isotropic seismic radiation field is required for this, and in typical underground mines noises are generated in only a few places, changing in time. However the scattering produced by tunnels and voids appears to generate a sufficiently isotropic field, even if only 30% of the noise sources are stable.

These results mean it is possible to accurately measure seismic velocity variations using both ambient and active source techniques using a standard geophone array. It should be possible to do this while simultaneously using the sensor array to perform passive microseismic monitoring.

Equations expressing changes in Young's modulus, E and Poisson's ratio, ν as functions of changes in P- and S-wave velocity have been derived. It appears that the elastic parameters, E and ν are more sensitive to velocity variations than might be expected, with changes in velocities producing larger changes in E and sometimes ν. This result further highlights the need for accurate monitoring of seismic velocity changes.

INTRODUCTION

Passive microseismic monitoring is a standard technique for many underground and open pit mines around the world (e.g. Mendecki[1997] and Lynch *et al.*[2005]). The recording of seismograms is triggered by the arrival of body waves generated by seismic events. These seismograms are typically classified manually as generated by blasts or fractures, or else they may be discarded as noise. If accepted as signatures of genuine fracturing, the seismograms are analysed to extract the source location and time as well as estimates of source parameters including inelastic co-seismic deformation (Potency: Ben-Menahem and Singh[1981], King[1978]) and radiated seismic energy. Generally, most analysis is focused on the event locations and source parameters, and those are examined to infer something about the rock mass itself. Some mines – mainly Polish coal and copper mines – do use passive tomography to study the medium (Lurka[2002, 2005] and Pfitzner *et al.*[2010]). Typically, double-difference tomography (Zhang and Thurber[2003]) yields estimates of seismic velocities accurate to a few percent.

Knowledge of how the body-wave seismic velocities v_P and v_S are changing in space and time yields information about the bulk effective elastic properties through the expressions (e.g. Aki and Richards[2002]):

$$v_P = \sqrt{\frac{\lambda + 2\mu}{\rho}} \,,$$

$$v_S = \sqrt{\frac{\mu}{\rho}} \,,$$

where μ and λ are the Lamé parameters and ρ is the rock density. Since μ and λ are related to Young's modulus E and Poisson's ratio ν by:

$$\lambda = \frac{E_\nu}{(1+\nu)(1-2\nu)} \,,$$

$$\mu = \frac{E}{2(1+\nu)} \,,$$

we have

$$E = \frac{\rho v_S^2 (3 v_P^2 - 4 v_S^2)}{v_P^2 - v_S^2} \,, \tag{1}$$

$$\nu = \frac{v_P^2 - 2v_S^2}{2v_P^2 - 2v_S^2}. \quad (2)$$

And, thus, if we can accurately measure the seismic velocities through a zone of rock, and we have a good idea of density (which would not generally change as mining progresses) we have the effective bulk elastic properties in different parts of the mine. These are rather useful for building accurate 3D models of the mine as input to static stress modelling codes.

Knowledge of seismic velocity variations can also indicate changing stresses: when stresses increase in a zone, some of the fractures perpendicular to the direction of maximum principal stress close, increasing the stiffness of the effective rock mass in that direction and thus increasing one or both of the body-wave seismic velocities. Decreasing stress results in lower velocities, but this can also be caused by an increase in the fracture density.

Unfortunately, the coupling between stress and seismic velocity is rather weak: values in literature (Niu *et al.*[2008], Yamamura *et al.*[2003], Sano *et al.*[1999] and Yukutake *et al.*[1988]) typically range between a relative velocity shift of 10^{-9}/Pa and 10^{-6}/Pa, varying between different rock masses. For typical underground mines, it seems reasonable to assume a value of around 10^{-8}/Pa. Thus a 1 kPa change in stress is expected to produce a change in seismic velocity of the order of 0.001% – far below the few percent resolution of passive tomography techniques. Note that an increase in stress is the only mechanism that can produce an increase in seismic velocity in a particular zone of rock over time, and so a 1% increase in velocity in a zone is implying that average stress increased by about 1 MPa in that zone.

The weak coupling with stress, and the fact that it would be desirable to monitor such stress changes, means that we wish to make routine seismic velocity measurements in working mines to an accuracy of at least 0.01% (10^{-4}).

This paper explores two recent approaches to the problem, using controlled and uncontrolled seismic sources. We also discuss differences between absolute and differential seismic velocity measurements and links to the effective rock mass elastic parameters.

CONTROLLED SEISMIC SOURCES

The controlled sources presented here (piezoelectric, eccentric rotating mass and pneumatic) have all been developed bearing in mind the constraints and practicalities of routine mine measurements:

- Accuracy. As discussed earlier, we would like to measure seismic velocity variations to a relative accuracy of about 10^{-4}.
- Range. We would like to be able to obtain hourly measurements of seismic velocity variations over a range approaching 1000 m (at least a few hundred meters) in order for interesting mine-scale problems to be monitored.
- Frequency. The dominant frequency radiated by the seismic source, f, should be less than 2 kHz so that standard geophones installed in mines for passive seismic monitoring could be used to receive source signals – it would be less convenient to install special accelerometers specifically for this purpose. The higher the frequency, the better the resolution in time and space as wavelength $\lambda = v_P / f$. However, for high frequencies the signal-to-noise ratio is decreased as attenuation will reduce the signal amplitude $a_{\max}$ at a source-sensor distance of R according to (Aki and Richards[2002]):

$$a_{\max}(\mathrm{R}) \sim \frac{\mathrm{a}_{\max}(0)}{R} \exp\left(-\frac{\pi f R}{v_P Q} \right).$$

- Borehole installation. Ideally, the controlled source should be able to be installed into a standard size borehole (NX – 76 mm internal diameter) at depths of up to 100 m.
- Reliable. The source should provide regular measurements of seismic velocity variations for at least two years.
- Cost. In order for this technique to be practical, the cost of a controlled source and associated control/timing unit should be comparable with the cost of a standard seismic station.

Piezoelectric

Piezoelectric sources have been successfully used in normal mining environments for a few years on an experimental basis (Lynch[2010, 2012]). These devices produce low amplitude seismic pulses which gives them an inherently low detection range. However, the high repeatability of piezoelectric sources allows the use of massive stacking to significantly boost effective range. A piezoelectric transducer can run continuously for long periods, making them suitable to study velocity variations in small areas over times of months or years.

The Cramér-Rao lower bound is the smallest possible time shift σ (which equates to velocity variation) that can be extracted from comparison of two highly similar but time-shifted signals with a given central frequency f_0 and signal-to-noise ratio (SNR^*), defined by the equation (Kay[1993] and Silver *et al.*[2007]):

$$\sigma \geq \frac{1}{2\pi \times f_0 \times SNR}. \quad (3)$$

The dominant frequency of a piezoelectric source is determined by the resonant frequency of the device – 1.6 kHz in our case. The SNR on the other hand will be

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*We use the strict definition of SNR: the ratio of root-mean-square signal to root-mean-square of the noise before the signal arrival.

dependent on noise sources present (electrical and seismic) and source signal strength. Stacking is effective at boosting SNR due to the effect of random (uncorrelated) noise growing by an average of $\sqrt{n}$, where n is the number of records stacked. The repeated (correlated) source signal on the other hand will grow by a factor n and so SNR is expected to grow by a factor of $\sqrt{n}$. This implies that the stacking will have diminishing returns as higher SNR ratios require much more data to be stacked, which in turn means longer periods between measurements of velocity variation (assuming data are collected at a constant rate).

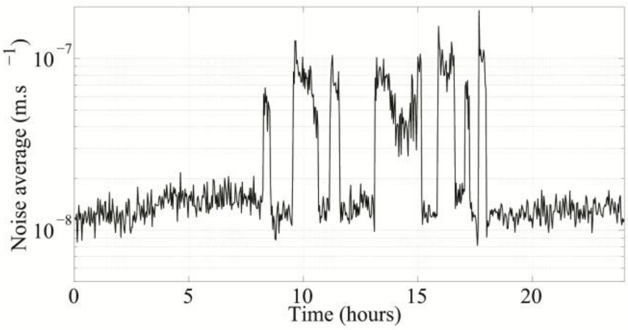

Figure 1. An example of noise history observed during a piezoelectric source experiment over the period of 24 hours. Active drilling in the area creates periods with noise levels that are an order of magnitude greater than that of quiet periods. These data were recorded in the Halo area of Ridgeway mine using a standard 14 Hz borehole geophone installed 80 m from the source

In a working mining environment, strong seismic noise generated by mining operations (heavy loading machinery, drilling, blasting, etc.) creates periods with significantly increased noise levels. Simple stacking of seismograms from such periods may contribute negatively to the SNR. To help contend with such noisy signals, a weighting system based on the noise values is applied to greatly reduce the record's contribution to the stack. As noise periods may vary greatly, the time duration required to record enough data to achieve a stacked seismogram with the desired SNR will vary as well. In addition to the weighting scheme, a cut-off may also be applied where records with noise values beyond a certain threshold are discarded.

Velocity variations are measured by calculating the time lag variation between stacks and a master stack which is created by stacking all data. The time lag can be calculated using time domain cross-correlation or phase shift calculation performed in the frequency domain. Any time lag variations induced by stress related changes will be significantly smaller than the smaller sampling period afforded by the data acquisition system (typically 10 μs). Spectral up-sampling was used to increase the inter-sample time resolution.

Advantages of the piezoelectric source over other sources include:

- Rapid pulse rate: the source can be fired 3 times per second.
- Low amplitude individual pulses: continuous firing of this source does not disturb collection of normal triggered seismograms by the passive microseismic monitoring system.

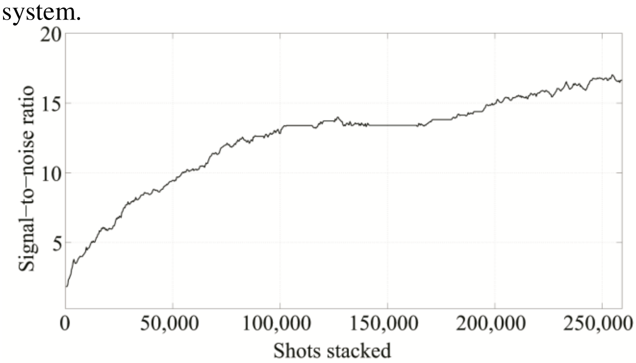

Figure 2. The SNR growth as a function of number of shots (individual measurements) stacked. The sensor was the same geophone as for Figure 1. The period of flat (slow) growth between roughly 100 000 and 200 000 shots corresponds to a period of very high noise causedby drilling (see Figure 1)

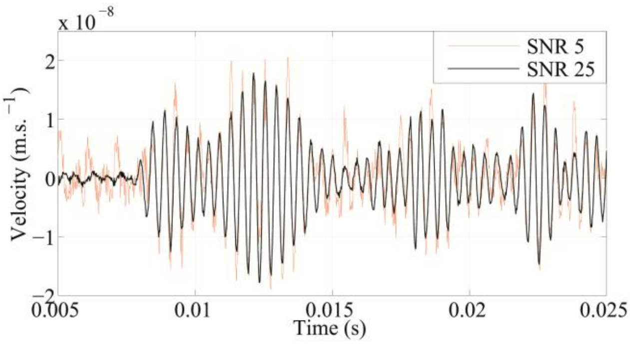

Figure 3. An example of the use of stacking to boost signal to noise ratio. The red curve denotes a stack that has a SNR of 5 while the black curve has an SNR of 25. To attain a signal to noise of 5 required the stacking of 3 960 shots (in a quiet period) whereas an SNR of 25 required 267 480 shots (this period had variable noise). This considerable difference in the data required is a result of the $\sqrt{n}$ growth rate of SNR through stacking and periods of high noise (see Figures 1 and 2). Scaling by the number of stacks added and their respective weighting factors creates the effect of the noise reduction. These data were recorded using the same geophone 80 m from the piezoelectric source

We observe a SNR of about 5 for the stacked seismograms in an average hour. From Equation 3 this implies that we should get a time resolution of about 2×10^{-5} s for variation measurements. The travel time for this P-wave over 80 m is about 80/5400 = 1.5×10^{-2} s and so we see that this source yields a relative accuracy of about 1.3×10^{-3} in hourly measurements of seismic velocity over an 80 m range. It should be noted that this particular rock mass at Ridgeway mine in Eastern Australia appears to be rather poor for transmission of these weak pulses: previous studies at El Teniente mine (Chile) and Mponeng mine (South Africa) have yielded much better accuracies of around 10^{-4} over 100–200 m with this type of source. The reason for this is probably that our experiment is situated close to the Ridgeway cave and close to many tunnels, and thus the medium we sample is within the fracture zone surrounding these excavations.

Eccentric Rotating Mass

A rotating eccentric mass seismic source differs from other seismic sources in that it produces a continuous sinusoidal signal as opposed to pulsed signals. Such monochromatic sources pose unique challenges when analysing data as the high degree of signal symmetry creates many unknowns.

The advantages of such a source include:

- Easy to grout into a borehole.
- Fairly inexpensive (less than a third of the price of a piezoelectric source).
- Sinusoidal data well suited to spectral analysis methods (e.g. Fourier transforms).
- Strong signals: Figure 5 shows that the ratio of peak power at 200 Hz to the 'noise' powers at other frequencies is about 1000. This implies the *SNR* for the signal amplitude would be $\sqrt{1000} \approx 30$ after only 1 second of recorded data.

There are two main disadvantages of such sources:

- The continuous monochromatic signal means the P- and S-waves would be inseparable at any fixed point. To properly analyse the signal requires a small phased array instead of a single standard mine sensor. Such a phased array would be at least 4 uni-axial geophones arranged in a 3D configuration about 10 m apart.
- We also need to measure the phase of the source, by using a sensor installed into the same hole.

Pneumatic

The pneumatic seismic source uses high pressure air to propel a 3 kg stainless steel mass within a 2 m tube to impact against a solid surface at the end. This makes it similar in nature to using a heavy hammer impact to generate seismic pulses. Such a device would require a 600 kPa air supply, supplied either by mine's internal supply or a standard dedicated air compressor.

A pneumatically powered device is attractive as a seismic source, due its high amplitude output and mechanical simplicity when compared to piezoelectric and eccentric rotating mass sources. However mechanical constraints require the device to operate at much lower duty cycles, firing only a few times per minute.

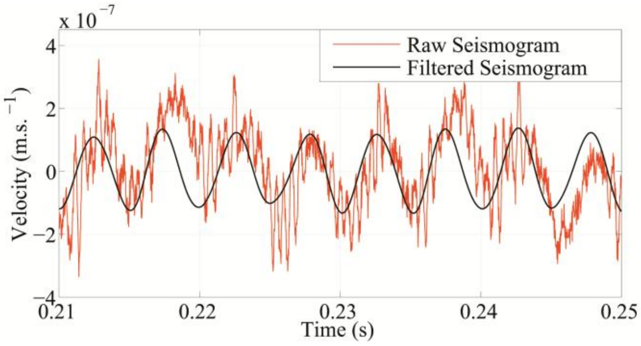

Figure 4. An example of the sinusoidal signal recorded by a geophone positioned 80 m away from the eccentric rotating mass source, operating in a working mine environment. The red curve denotes the raw unprocessed signal while the black curve denotes the same signal, bandpass filtered between 150 and 300 Hz. The seismic source has an operating frequency of 200 Hz

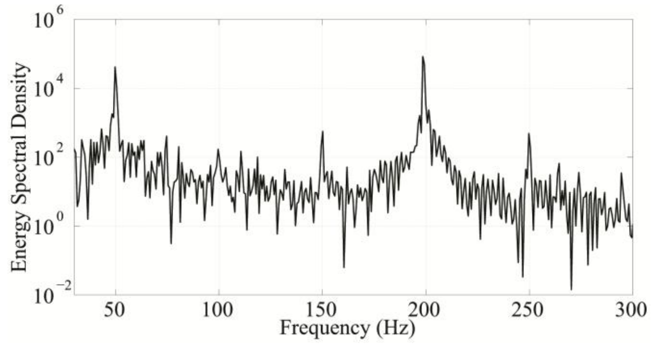

Figure 5. A spectral plot of 60 seconds of data generated by the eccentric rotating mass source. A dominant frequency of 200 Hz is evident which is the operating frequency of the source. Typical mains electrical power interference at 50 Hz is also present on the raw signal

We have developed a prototype of such a source and installed at the experimental zone at Ridgeway with the aim of testing seismic amplitude output and signal reproducibility. Figure 6 shows an overlay of a series of shots generated by the pneumatic source prototype, recorded by the geophone 80 m away. The strong signal repetition and high amplitude output is rather encouraging as it implies that stacking can be used to improve *SNR* for the signals from this source. The dominant frequency emitted by this source is about 1550 Hz, but there is significant power radiated between 1200 Hz and 2600 Hz.

Assuming we run this source 4 times per minute, we could stack 240 shots per hour. This would produce a stacked seismogram with *SNR* of 140 which would allow us to estimate relative velocity variations of about 5×10^{-5} at a range of 80 m. Ignoring inelastic scattering, this implies a resolution of 10^{-4} at a range of 160 m, which is getting close to meeting our aims.

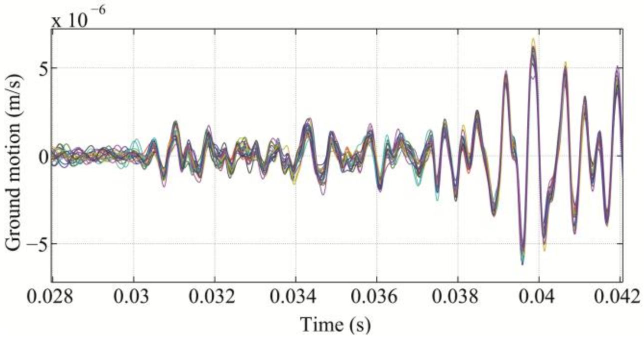

Figure 6. A series of shots from a prototype pneumatic seismic source, showing the highly repeatable nature of each shot. The highly repeated signal allows for easy stacking of individual shots which in turn boosts effective range. Each shot has a SNR of about 9 measured over a distance of 80 meters

AMBIENT SEISMIC NOISE

Using ambient seismic noise to continuously monitor the elastic properties of the earth's interior has become an increasingly popular method in crustal seismology and volcanology (Ballmer *et al.*[2012], Brenguier *et al.*[2008, 2011], Duputel *et al.*[2009], Durand *et al.*[2011], Lawrence and Prieto[2011], Moschetti *et al.*[2007], Poli *et al.*[2012] and Shapiro *et al.*[2005]). The technique relies on cross-correlating continuously recorded seismograms between pairs of sensors, and yields information about the elastic properties between these two sensors. In crustal studies the noise is dominated by surface waves emanating from the interaction of the ocean with the solid earth. In an underground mining environment this is not the case, since the strength of these surface waves decrease rapidly with depth. The noise is instead dominated by vibrations associated with mining activities – drilling, pumping, scraping, etc. – which are generally rather localised, short lived and spatially unstable.

The seismic Green's function can be retrieved by cross-correlating ambient seismic noise between seismic sensors – this has been theoretically proven for an anisotropic medium in the presence of an infinite number of noise sources (Wapenaar[2004]). This result does not imply that the full seismic Green's function can be retrieved by cross-correlating ambient seismic noise generated by mining activities, since mining noises are usually dominated by a few singular sources: development ends, working stopes, ore-passes, etc. Conveniently, it has been shown that the full seismic Green's function is not a necessary condition to accurately monitor seismic velocity variations (Hadziioannou *et al.*[2009]). However, in that work the authors showed that, in the presence of a limited number of sources, the error in the measurement is strongly related to the temporal stability of the dominant sources. This may be a problem because in a mining environment, unlike in crustal studies, the location of the dominant noise sources is not necessarily stable – for example, a drill operates intermittently at a particular location throughout the day. The absence of stable sources in mines might be overcome by the fact in an underground mine there exists many strongly scattering surfaces, such as voids, tunnels and stopes. Each of these scatterers will in essence act as a seismic source, and since they are spatially and temporally stable (tunnels don't move!) we have reason to believe that a stable seismic wave field might be generated by mining noises. If so, this ambient noise technique could be applied in working mines to determine velocity variations to the desired accuracy.

Numerical Experiment

To test whether this technique is applicable we conducted a mine scale numerical experiment with a finite-difference seismic wave field modelling code (Mendecki and Lötter[2011]), with realistic mine plans and actual records of mine seismic noise. Mine plans from Beaconsfield mine, in Tasmania (Australia) were used to construct a 1 × 1 × 0.5 km model with 1 m grid spacing that consisted of solid rock (density $\rho = 2700\,\text{kg/m}^3$, inelastic attenuation $Q = 300$), broken rock ($Q = 30$) and air – see Figure 7. In the model the background medium was constructed with solid rock, while the tunnels were filled with air and surrounded by a 2 m fracture zone consisting of broken rock. Noise sources were placed at 10 random locations, with actual recorded noise used as the source time function (see Figure 8). The noise was recorded in an area close to where drilling was taking place; upon closer inspection the individual shots of the hammer drill are clearly visible. The dominant frequency of each of the impacts is around 1500 Hz, and the other noise sources between 10 and 2000 Hz.

To investigate whether the result found by Hadziioannou *et al.*[2009] is also valid in a mining environment, i.e. if only a finite number of sources is sufficient to determine seismic velocity variations, we compute synthetic seismograms at two stations and cross-correlate them to find an estimate of the seismic Green's function – in this case we correlate the z-components so we actually construct the zz-component of the Green's tensor. Then the background medium is perturbed by an increase in seismic velocity of 0.01% and the process is repeated. The travel time variation is then determined by the moving window cross-spectral technique (MWCS) (Clarke *et al.*[2011]). In Figure 9 the result of the process is shown. From the asymmetry in the cross-correlation functions (CCF's) it is clear that the full seismic Green's function is not recovered yet. The peak of the correlation function is present at negative lag-time; this indicates that the majority of the seismic energy was travelling from sensor B to sensor A, which from the position of the noise sources seems entirely possible. Very little difference is noticeable in the CCF's for the two cases, but by using the MWCS technique the relative travel time variation is correctly determined.

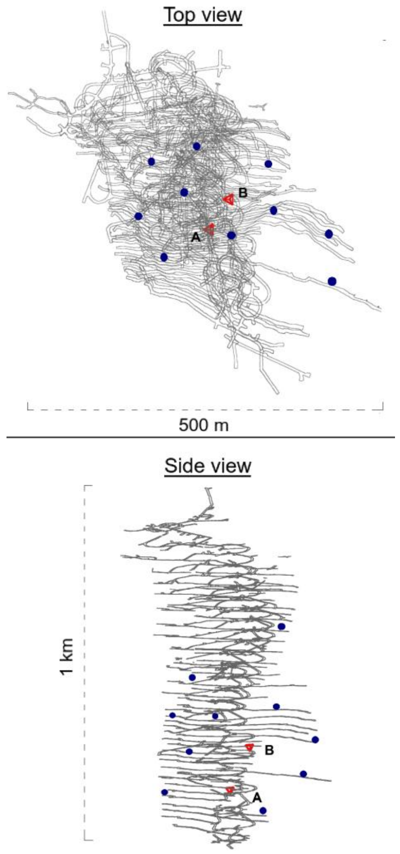

Figure 7. Mine plans from Beaconsfield Mine (Tasmania, Australia) used to construct the numerical model. The black triangles represent the sensor positions that were used to record synthetic data. The sensors are roughly 100 m apart. The letters A and B indicate the positions of the noise sources (drilling, in this case) that generated the ambient noise

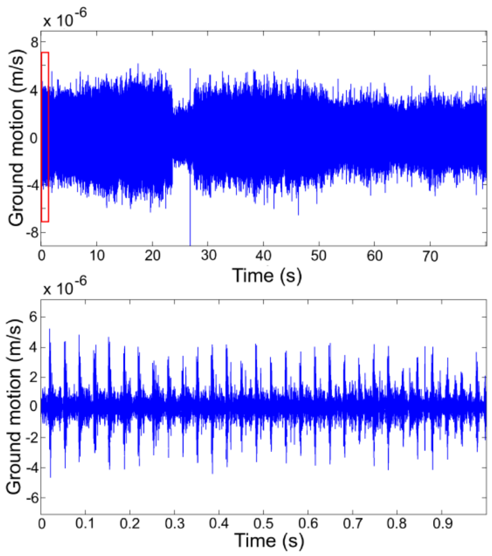

Figure 8. Two minutes of noise recorded in an active mine (top), with an expanded view of the first second shown bottom. Initially the signal seems random, but upon closer inspection it is clear that the signal is dominated by drilling that was happening close (approximately 30 m) to the seismic sensor. This is the seismogram we used as our source time function in the numerical experiment

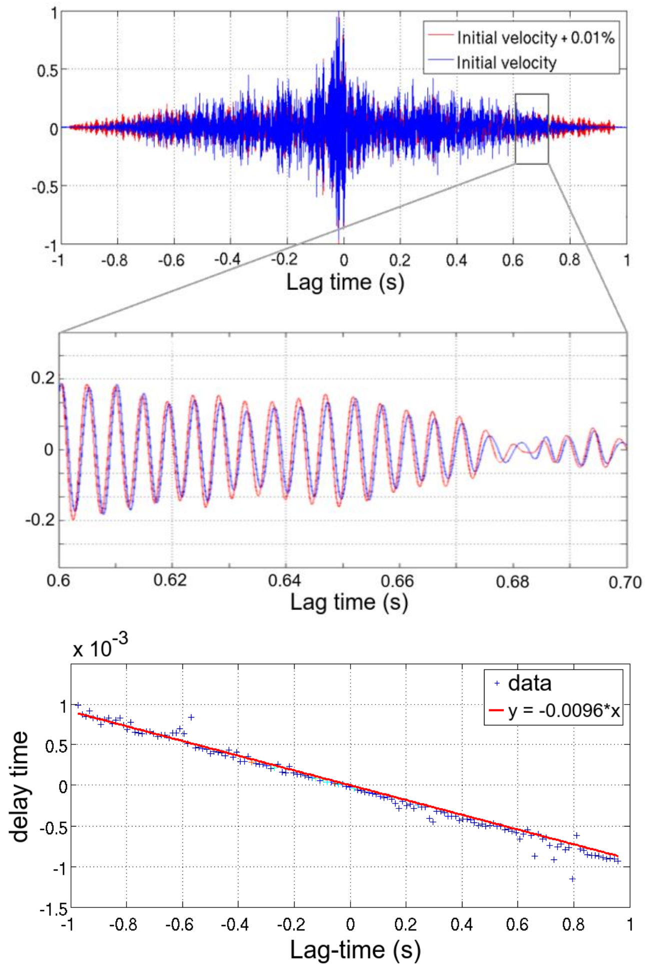

Figure 9. The cross-correlation obtained from the synthetic seismograms for the initial velocities together with the correlation obtained when the velocity of the background medium is increased by 0.01% (above). Application of the MWCS technique (below), successfully recovers the travel time decrease associated with this increase

Stability of Noise Sources

Now that we are confident that the technique is applicable in a mining environment, we want to investigate what effect the temporal stability of noise sources will have on the accuracy of our measurements. To do this we follow the same approach as mentioned in Hadziioannou *et al.*[2009] namely we will randomly turn off noise sources – behaviour we would expect from drilling, etc. in mines – and compare travel time variations taken during these times with measurements taken while all the sources were active. The relative error in the measurement as a function of the percentage of active noise sources is shown in Figure 10. We see here that even when only 30% of the initial noise sources were active, a relative error of only 5% is made. This is due to the tunnels and excavations, which essentially account for a stable seismic wavefield. When less than 30% of the noise sources are active, the seismic energy is not enough to excite all the scatterers and as a result the wavefield has not converged to a stable state.

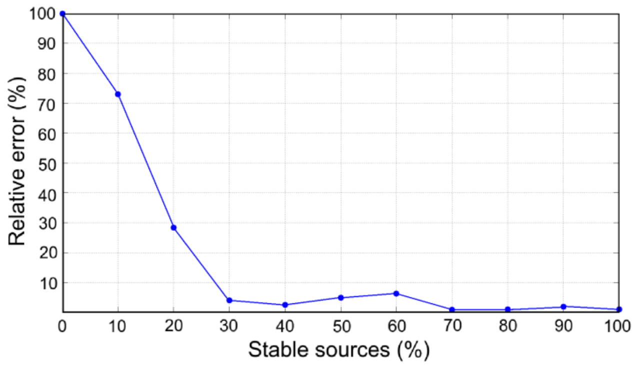

Figure 10. The relative error in the determination of the travel time variations as a function of fraction of time-stable sources. The figure shows that not many stable noise sources are needed to accurately retrieve the seismic velocity variations

ABSOLUTE AND DIFFERENTIAL VELOCITY MEASUREMENTS

Equations 1 and 2 show how to relate measurements of v_P and v_S to the physical parameters E and ν (assuming knowledge of an invariant density ρ). However, all of the techniques discussed in this paper are interferometric and so yield accurate information about the differential velocity: that is, how the velocity has changed between two times of measurements. How does knowledge of differential velocity δv_P and δv_S relate to the elastic parameters? For any two-parameter function $f(x, y)$ we have the general expression for a small change in the parameters δx and δy:

$$\delta f = \frac{\delta f}{\delta x}\delta x + \frac{\delta f}{\delta y}\delta y$$

Applying this to Equation 1 we obtain the following expression for the relative change in Young's modulus $\delta E / E$ as a function of the relative changes in body wave velocities $\delta v_P / v_P$ and $\delta v_S / v_S$:

$$\frac{\delta E}{E} = \frac{2v_P^2 v_S^4}{(v_P^2 - v_S^2)(3v_P^2 v_S^2 - 4v_S^4)}\left(\frac{\delta v_P}{v_P}\right) + \frac{6v_P^4 v_S^2 - 16v_P^2 v_S^4 + 8v_S^6}{(v_P^2 - v_S^2)(3v_P^2 v_S^2 - 4v_S^4)}\left(\frac{\delta v_S}{v_S}\right).$$

For the special case of a Poissonian solid ($\nu = 0.25$, $v_P = \sqrt{3} v_S$) this equation becomes

$$\frac{\delta E}{E} = 2\frac{\delta v_S}{v_S}$$

and so we see that a 1% change in S-wave velocity would correspond to a 2% change in effective Young's modulus.

In a similar manner we obtain an expression for relative change in Poisson's ratio as a function of relative changes in body wave velocities:

$$\frac{\delta \nu}{\nu} = \frac{2v_P^2 v_S^2}{(v_P^2 - 2v_S^2)(v_P^2 - v_S^2)}\left(\frac{\delta v_P}{v_P} - \frac{\delta v_S}{v_S}\right)$$

For the special case of the Poissonian solid we obtain $\delta \nu / \nu = 0$, as expected.

However, for a typical case of $v_P = 5500$ m/s and $v_S = 3500$ m/s, we have

$$\frac{\delta \nu}{\nu} = 7.2\left(\frac{\delta v_P}{v_P} - \frac{\delta v_S}{v_S}\right)$$

and so if there a 1% *increase* in P-wave velocity together with a 1% *decrease* in S-wave velocity, the Poisson ratio would increase by over 14%.

CONCLUSIONS

It appears possible to use either piezoelectric, rotating mass or pneumatic sources to monitor relative changes in seismic body wave velocities in working underground mines to a resolution of around 10^{-5} to 10^{-3}. At these levels, the Earth-tides and atmospheric pressure changes should just be detectable, and any future work on correlating velocity changes with mining activities should compensate for these well-known effects. Key is the trade-off between range and accuracy: a longer sensor-source distance leads to weaker signals which produce less precise estimates of velocity variations. Also important is the required period of measurement: if daily estimates of velocity are required instead of hourly estimates, the *SNR* will be $\sqrt{24}$ higher, leading to an increase of the accuracy by the same factor.

In a highly attenuating medium such as the rock mass within the Ridgeway cave's fracture zone, it appears possible to measure hourly velocity changes with an accuracy of 10^{-5} over distances of 80 m using standard borehole geophones typically used for passive microseismic monitoring, using a pneumatic source. All of the evaluated seismic sources produce highly repeatable signals, and so it is possible to remove these signals from normal triggered seismograms, i.e. perform active and passive seismic monitoring simultaneously using the same array of seismic sensors.

Considering a range of factors including signal strength and use of normal geophones as the receiver, it appears that the pneumatic source is the preferred seismic source for active monitoring. However, reliability of this type of source has not been established at this time: future work will address this.

A different approach to accurate measurements of seismic velocity variations involves the use of ambient seismic noise, of which there is usually plenty in working mines. This study used actual recordings of noise with a 3D numerical model of the Beaconsfield mine to demonstrate that only a few sources of noise combine with the strong scattering nature of the tunnels and mining voids to produce an effective isotropic seismic radiation field. This field proves sufficient to measure seismic velocity variations of the order of 10^{-4} in this numerical modelling example. The use of ambient noise to measure subtle changes in body wave seismic velocities therefore seems applicable in a typical mining environment. Initial results using actual recorded data in a working underground mine (Olivier *et al.*[2012]) have also indicated a resolution of around 10^{-4} using this technique. This approach is particularly attractive, as it does not require any controlled seismic source hardware. All that is required is continuous seismic records from the standard seismic array and a sufficiently developed seismic radiation field. The continuous data are recorded at the same time as normal passive seismic monitoring (recording of triggered seismograms) is taking place.

Lastly, the expressions for the change in elastic parameters as functions of the measured changes in P- and S-wave velocity demonstrate that the elastic changes are stronger than the velocity changes. For example, to reliably detect changes in Young's modulus of 1%, we need to reliably measure velocity changes at the level of 0.5% in a typical rock mass. The Poisson's ratio sensitivity can be much stronger in some cases. This highlights the need to monitor the P- and S-wave changes as accurately as possible.

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