AEGC2019
Data to Discovery
Australasian Exploration Geoscience Conference
2-5 September 2019 • Perth, Western Australia
Incorporating the AIG, ASEG, PESA and WABS

The effects of seismic anisotropy on mining seismology

Andrew King
CSIRO
Kensington WA 6151
Andrew.king@csiro.au

SUMMARY

Microseismics – the detection and characterisation of mining-induced fracture events in the rockmass – is widely used to improve geotechnical understanding of the rockmass response to mining, and for hazard assessment of rockbursts and roof falls. These uses of microseismics require that the seismic events be accurately located, which can only be done using an accurate velocity model.

In sedimentary environments, seismic velocity is typically anisotropic, usually being somewhat faster in a horizontal direction than in the vertical direction. However, anisotropy is seldom taken into account when processing microseismic data, resulting in locations of seismic events which can be significantly in error.

This paper presents a technique for inverting a set of calibration shots with known location, along with a set of mining-induced seismic events, for an anisotropic velocity model. An example of the differences in event location is shown, illustrating the potential geotechnical significance.

Key words: seismic anisotropy, mining seismology.

INTRODUCTION

Mining seismology involves the detection of fracturing events in the rockmass caused by stress changes due to the mining process. The location of these events yields useful geotechnical information about how the rock is responding to the mining process, which in turn is used to inform hazard assessment tools, particularly regarding the dangers of rockburst or roof fall.

Seismic anisotropy occurs where the velocity of seismic waves depends on the direction of propogation. The most common cause is sedimentary layering, which results in seismic velocity being higher in a horizontal direction than in the vertical direction. But other kinds of anisotropy also exist, caused by the presence of multiple parallel joints or fractures, for example.

Mining seismology was developed in deep, hard-rock mines, where anisotropy is usually small and can be neglected. However, mines in sedimentary rocks, such as coal mines, face a different situation. Here S-wave splitting, where vertically and horizontally polarised S-waves travel at different velocities, can be significant, with velocity differences of 30-40% being common. This observation implies that P-wave velocities will depend on the elevation angle of the ray path.

METHOD AND RESULTS

The seismic data shown in this paper are from a longwall coal mine in central Queensland. The geological section contains layers of siltstone and fine-grained sandstone, as well as several thin coal seams in addition to the seam being mined. Only small variations in velocity were seen in downhole sonic logs, so we assumed that the velocity could be modelled as homogeneous, but anisotropic, and that a vertically transverse isotropic (VTI) model would be appropriate. This model requires five parameters for its specification, for which Thomsen's formulation (Thomsen, 1986) has been chosen. The P, SV (vertically polarised S) and SH (horizontally polarised S) velocities, as a function of elevation angle, are:

$$v_P^2(\theta) = \alpha_0^2\left[1 + \epsilon \sin^2\theta + D^*(\theta)\right]$$

$$v_{SV}^2(\theta) = \beta_0^2\left[1 + \frac{\alpha_0^2}{\beta_0^2}\epsilon \sin^2\theta - \frac{\alpha_0^2}{\beta_0^2}D^*(\theta)\right]$$

$$v_{SH}^2(\theta) = \beta_0^2\left[1 + 2\gamma \sin^2\theta\right]$$

where α_0 and β_0 are the vertical P and S wave velocities, θ is the elevation angle of the wavefront, and ε and γ are the degrees of anisotropy of the P-SV and SH phases respectively.

These velocities are phase velocities, and are given as functions of the phase angle rather than the group angle ϕ. The angles are related by

$$\tan\left(\phi(\theta)\right) = \left(\tan\theta + \frac{1}{v}\frac{dv}{d\theta}\right) / \left(1 - \frac{\tan\theta}{v}\frac{dv}{d\theta}\right)$$

The group velocity is given by

$$V^2\left(\phi(\theta)\right) = v^2(\theta) + \left(\frac{dv}{d\theta}\right)^2$$

For locating mining-induced seismic events, it is the group angles and velocities that we need to use. I am not aware of any closed-form expressions for group velocity in terms of group angle (Fowler, 2003), so this is done numerically, by first interpolating the phase angle given the ray angle, and then computing the group velocity.

Determination of Anisotropy from Microseismic Data

Anisotropic parameters are determined using arrival times from calibration shots with known locations. The picked arrival times also need to have uncertainties associated with them, so that more-confident picks can be more-strongly weighted in the inversion process. S wave arrivals are difficult to pick on shot data, however, so it is helpful to include a few shear-failure type seismic events with strong S-wave arrivals, and to simultaneously invert for their locations along with the velocity model. The seismic data are rotated into P-SV-SH traces to enable the two S phases to be picked individually.

Example Microseismic Data Set

An example seismic event arrival at a triaxial geophone is shown in figure 1. The traces have been rotated into a P-SV-SH orientation, and the difference in arrival times between the SV and SH phases can clearly be seen.

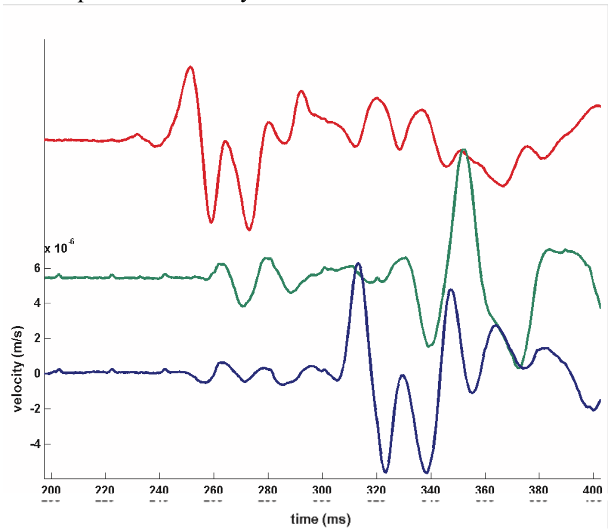

Figure 1. Example seismic event, shown rotated into P (red) – SV (green) – SH (blue) directions.

The geophone array for this experiment consisted of 20 triaxial geophones grouted in four boreholes in strings of five. Six calibration shots were fired into the array, from three different locations. Two mining-induced fracture events were also used, due to the difficulty of picking S arrivals on shot data.
The resulting velocity model is shown in the form of velocity curves as a function of elevation angle in figure 2.

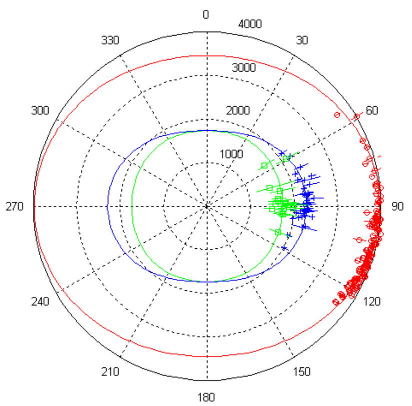

Figure 2. Inverted velocity model, showing velocity as a function of ray angle, for P (red) – SV (green) – SH (blue) phases. The picked arrivals are shown superimposed

To give an idea of the significance of this result, the locations of a selected set of microseismic events are shown in figure 3, plotted using an isotropic velocity model and the anisotropic model result. The difference is significant: note the large cluster of events that plots below the mined seam in the isotropic locations but has shifted above the seam in the anisotropic results. These sorts of differences potentially have significant impact on the geotechnical interpretation.

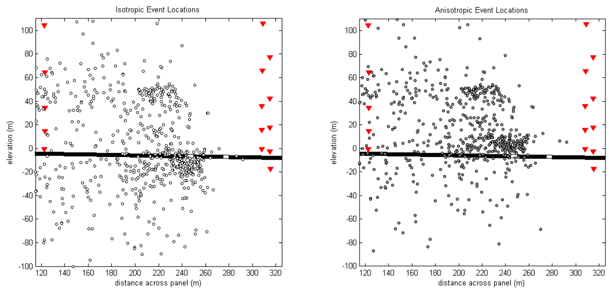

Figure 3. The effect on event location of using an isotropic (left) versus an anisotropic (right) velocity model. This is a section view with the coal seam being mined shown in black.

CONCLUSIONS

Anisotropy, if not properly accounted for, can cause large errors in seismic event location, as demonstrated in the example. This degree of anisotropy is typical of what is seen in microseismic experiments in coal mines, so these errors are probably typical. We have shown how the use of a few calibration shots of known location, augmented with a few mining-induced shear events with clear S-wave arrivals, can be used to derive an anisotropic velocity model, which potentially yields significant improvements in event location. This particular location had small enough velocity variation across different stratigraphic units that a homogeneous model was deemed adequate, but in more complex areas, each layer could potentially have its own anisotropy parameters.

REFERENCES

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