Acoustic impedance inversion for geotechnical evaluation in underground coal mining

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Summary

In underground coal mining, knowledge of the geomechanical properties of the strata surrounding the mining horizons is essential for the prevention of unexpected rock failures that can disrupt production and jeopardize mine safety. Model based acoustic impedance inversion integrates drill hole and seismic information to allow assessment of the geomechanical environment. We demonstrate our approach using results from a 3D and a 2D seismic survey. We introduce a means of converting acoustic impedance to the Geophysical Strata Rating (GSR). The GSR is a rock mass rating scheme that is normally derived from geophysical logging data. When expressed in terms of GSR, acoustic impedances have values that are meaningful to coal mine engineers.

Introduction

In underground coal mine exploration, there is a well accepted role for seismic reflection surveying to locate geological structures. Mining into unexpected structures can cause significant and costly delays to the operation of the longwall mining equipment that most mines now employ. To a large extent, Australian mines where 3D seismic surveys can be successfully conducted, can plan their operations with reasonable understanding of the structural constraints. An outstanding problem, however, concerns the prediction of the geotechnical conditions likely to be encountered during mining.

Geotechnical conditions determine the extent to which mine tunnels need to be supported by rock bolts, cables, steel straps and mesh. The mining also needs to consider the strengths of higher layers and whether they will progressively collapse into mined out areas, thus relieving stresses, or whether they will remain standing and exert excessive loads onto the mine faces and pillars.

Geotechnical investigations conventionally involve analysis of core samples, computer modeling and application of design criteria. In Australia, there is also considerable use of geophysical logs to assess rock conditions. Hatherly et al (2008a) have introduced the Geophysical Strata Rating (GSR) which provides a rock rating on a linear scale between approximately 20 (weak rock) and 100 (strong rock) similar to the Rock Mass Rating (Bieniawski, 1989) and the Coal Mine Roof Rating (Mark and Molinda, 2005). These schemes are based on observations and rock testing. Another scheme utilizes a rating known as the Q-value. For this, Barton (2002) introduced a relationship between Q-value and seismic velocity, depth and porosity.

Our current research (Hatherly et al, 2008b), has involved an investigation into the possibility of estimating geotechnical properties from acoustic impedances obtained from the inversion of seismic reflection data. If this can be done, then seismic reflection data can be used to assist with the overall assessment of geotechnical conditions.

Model based acoustic inversion

For our work, we have used the model based acoustic inversion software available in the CGGVeritas, Hampson-Russell package. Model based inversion is well suited for the inversion of coal mine seismic survey data because of the availability of drill hole data. The number of holes drilled at a mine varies according to the geological complexity and the cost (depth) of drilling. For deeper mines (500 m), the drill holes might be at 500 m spacings. For the shallower mines which operate at about 200-300 m depth, typically found in Australia, drill holes can be as close as 150 m. Regardless, over the area of a few square kilometers that is typical of a 3D seismic survey, numerous holes will have been drilled. This allows generation of a good starting model.

Within the Hampson-Russell model based inversion, the software allows use of high frequency and low frequency starting models. The idea with the low frequency model is that the model represents geological data at frequencies below the frequency content of the seismic data and that the higher frequency information will then be provided by the inversion. With the high frequency starting models (or, more accurately, broad-band models), the model contains both the low and higher frequency components. For these two types of starting models, there is then the option of utilising hard or soft constraints in the inversion process. The hard constraint allow for the best solution within a specified range of the impedances in the starting model. The soft constraints penalize possible solutions according to their difference to the starting model.

With a low frequency starting model, the result needs to draw heavily upon the seismic data and hard constraints are preferable. Inversion with a high frequency starting model needs to more closely honour the starting model and inversion utilizing soft constraints is preferable.

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We have experimented with both types of models. However, given the large number of drill holes typically available at coal mines, high frequency starting models can usually be constructed and give the best results.

Geophysical Strata Rating (GSR)

The GSR (Hatherly et al, 2008a) is an empirical scheme based on sonic velocity and values for the porosity, clay content and quartz content derived from geophysical logging data. In keeping with other rock mass classification schemes, the GSR considers the properties of the intact rock and also the defects within the rock mass. The sonic (P-wave) velocity is the main component of the GSR. The sonic derived factor is then adjusted according to the porosity (porous rocks are weaker) and clay content (clay-rich rocks are weaker). For the defects, contacts between beds are indicated by variability in the clay content and the velocity. The fact that velocity is also affected by fractures is incorporated as well.

Figure 1 shows a comparison between acoustic impedance calculated from geophysical logs and GSR values. These data are from 4 exploration drill holes from different regions of the coal fields of eastern Australia. Shown by the triangles is an empirical relationship suggested for this association between acoustic impedance and GSR. The relationship allows impedance values to be expressed in terms which are meaningful to geotechnical engineers.

For acoustic impedances less than 8.9:
GSR = (100 x impedance – 560)/6

For acoustic impedance greater than 8.9:
GSR = (83 x impedance – 145)/10.8 (Equation 1)

Acoustic impedance is measured in unit of t/m^3-km/s.

Example 1 - 3D survey

Our first example involves the inversion of 3D seismic data from a coal mine in Queensland. Three separate surveys had been undertaken and the results were combined to provide a single volume. After true amplitude processing, coal seam reflectors were picked and combined with acoustic impedances from 20 drill holes to produce a high frequency starting model (see Figure 2). The plan view of the survey area and the locations of the drill holes are shown in Figure 3.

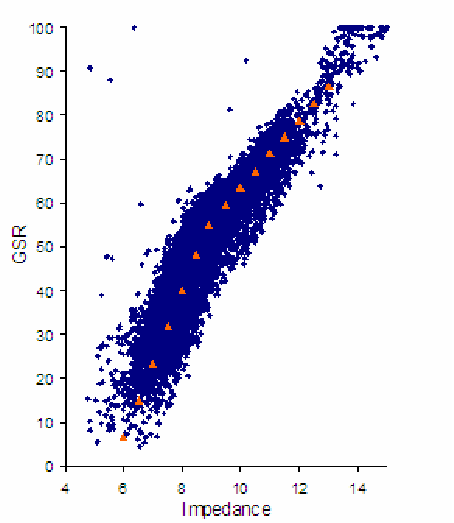

Figure 1: Plot of GSR against acoustic impedance. All values are derived from drill hole geophysical logs with the depths of the holes generally less than 300 m. The data are from 4 holes from Australian coalfields and there are over 8000 points present. The triangles show the empirical relationship between GSR and acoustic impedance given by Equation 1.

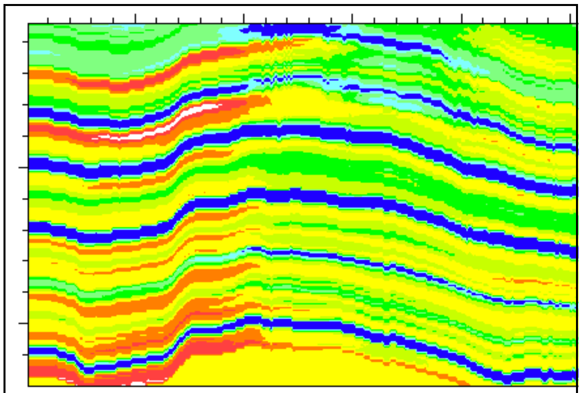

Figure 2: Vertical section through a high frequency impedance model taken from a 3D seismic survey. Impedance values range from 3.5 to 12.3 t/m^3-km/s (blue to white). Coal seams are blue horizons. Two-way reflections are between 55 and 170 milliseconds. Horizontal distance is approximately 1.8 km.

In order to maintain similarity with the starting model, the inversion was undertaken utilising soft constraints. Figure 3 shows the average impedances derived from the inversion for a 5 millisecond thick section immediately above the main coal seam (approximate thickness of 10 m). The impedances have been converted to GSR using Equation 1.

It can be seen from the results that the region with the elevated values of GSR in the SW corner coincides with the higher impedances in the left hand section of the starting model, Figure 2. Overall, most of the broad-scale changes in GSR shown in Figure 3 are also present in the starting model. The effect of the inversion has been to provide detail missing in the initial high frequency model.

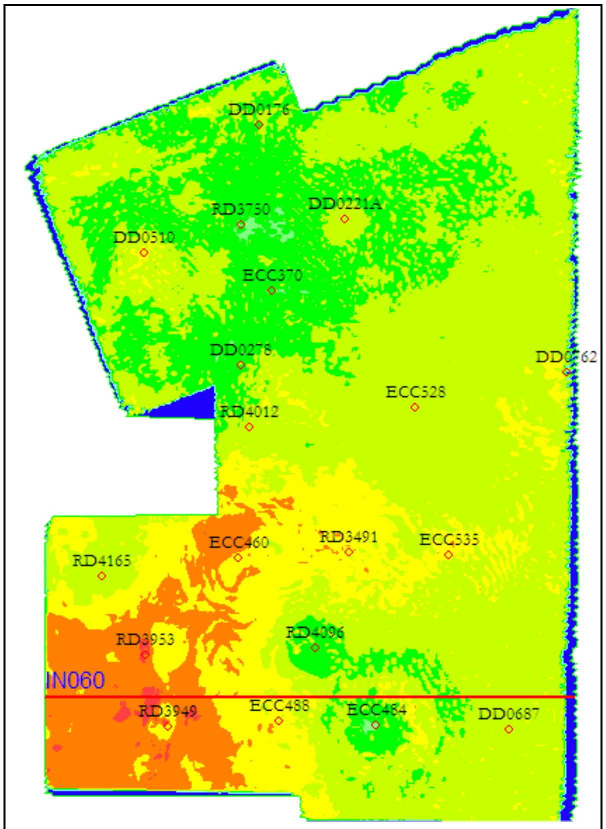

Figure 3: Plan view of average GSR values determined by acoustic impedance inversion utilising a high frequency starting model and soft inversion constraints. Impedances were converted to GSR using Equation 1. This figure shows the average GSR values for a 5 millisecond interval in the coal seam roof immediately above the main coal seam (bottom coal seam in Figure 2). GSR values range from 30 (green) to 90 (red). The location of the section of the starting model shown in Figure 2, is also indicated. All drill holes were used for the construction of the starting model. The dimensions of this survey are approximately 1.8 km by 2.9 km.

From the perspective of mine planning and operations, knowledge of rock properties for a 10 m roof section allows areas of weaker roof requiring additional support to be indentified. Other intervals in the inversion results can also be interrogated to assess whether there are abnormal regions higher in the geological sequence or below the working seam.

For detailed mine planning, however, engineers also seek information on rock properties over intervals of a meter or less. Unfortunately, the frequency content of reflection seismic data is such that the inversion results are not able to provide information at this scale. The detailed information must therefore come from other sources, such as shallow inspection holes drilled in the mine roof. Nevertheless, the seismic data are extremely useful for providing an overall geological framework for the geotechnical assessment.

Example 2 - 2D survey

The second example concerns the inversion of a 2D seismic line with only one drill hole available for the construction of the starting model. Three reflectors picked from the seismic line cover the interval of interest but with only one drill hole, the inversion called for a low frequency starting model with the hope that the inversion would then introduce all of the required higher frequency components from the seismic data. Figure 4 shows the low frequency starting model. The results of the inversion with hard constraints are shown in Figure 5.

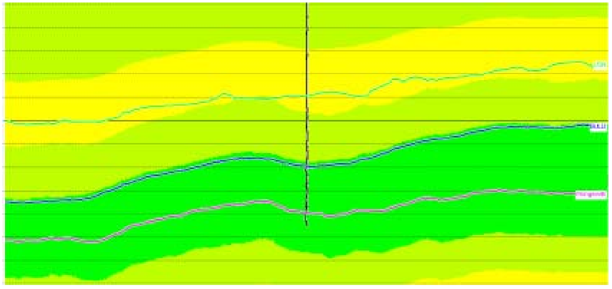

Figure 4: A low frequency starting model utilising the reflection times for 3 horizons (bottom 2 are coal seams) and a single drill hole in the centre of the line. This line is 2 km in length. The reflection times are between 150 and 270 milliseconds. Impedances are in the range 8.4 to 10.5 t/m^3-km/s (green to yellow). To the right of the drill hole, the coal seams separate as a result of silling in the lower seam which is up to 30 m thickness.

It can be seen that the coal seams have been successfully introduced by the inversion. The impedances are a higher than actual coal impedances but it is encouraging to see that this aspect of the inversion was successful.

This line also had a geological target in the form of a sill that intruded the bottom coal seam to the right hand part of the section. The sill was less than 1 m thick at the drill hole but there is an increase in the separation of the bottom two reflectors to the right of the drill hole that is interpreted to indicate that presence of the thickening sill. Drill holes drilled elsewhere into the sill showed that it can reach thicknesses of at least 30 m and that the sill material is extremely hard (impedances greater than 15 t/m^3-km/s).

In Figure 5, it can be seen that the inversion result has indicated the presence of an anomalous region to the right of the drill hole but the impedances are not indicative of the expected hard material. Just as the impedance of the coal seams has been over-estimated, the impedance of the sill has been under-estimated.

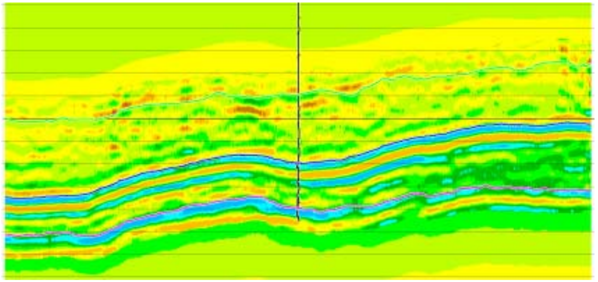

Figure 5: Results of acoustic impedance inversion utilising the starting model in Figure 4 and hard constraints. The reflection times are between 150 and 270 milliseconds and the impedances are between 6.4 (blue) and 12 (brown) t/m^3-km/s. While three coal seams have been correctly inserted, their impedances are probably too high and the impedance of the expected hard sill to the right of the section is lower than expected.

To achieve a better mining result, more drill holes are required. However, this example does provide a good illustration of the use of a low frequency starting model and inversion using hard constraints.

Discussion

In this paper we have concentrated on the main issues involved in producing good inversion results for seismic reflection surveys at underground coal mines. There are other issues that also need to be considered such as true amplitude processing, the extraction of the source wavelet and the criteria used to select the optimum model. For land seismic data such as this, considerable effort was required to treat the noise (spikes and low frequency surface waves) in the raw field data. Once this was done, surface consistent scalars were used to adjust the balance of the seismic traces. Stacking and post-stack operations then provided adequate treatment of the remaining noise. Wavelet extraction did not prove to be a significant issue and for the model testing, we made extensive use of cross-validation and correlation assessments of both the impedances and seismic traces.

For each of our inversion studies, a number of solutions were produced and our final choice was based on the match of the drill hole and seismic data from both a geological perspective and consideration of the goodness of fit. To properly consider these options, there is a need for close cooperation between seismic professionals and mine staff.

We also have found that the integration of drill hole and seismic data that occurs through seismic inversion assists in bridging the discipline gaps between geophysics, geology and engineering. Geologists frequently construct geological models on the basis of boundaries drawn between drill holes but give little consideration to the positions of the boundaries shown by seismic surveys. The model building involved in seismic inversion allows integration to occur. Another attraction for the inverted data is that through the inclusion of low frequency components, the inverted results take on the appearance of a geological section. It is easier for non-specialists to assess the subsurface geology from an impedance section than it is from a conventional seismic display.

Conclusion

Acoustic impedance inversion utilizing a model based approach has proved to be a worthwhile process for improving the understanding of the ground conditions in underground coal mining. The mapping of reflectors allows identification of structures that might affect coal seam continuity. Acoustic impedance inversion complements this by estimating the rock properties. If the acoustic impedances are converted to GSR values, the results are in terms that are meaningful for geotechnical activities. Acoustic impedance inversion provides a useful way for integrating seismic and drill hole data.

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