Overburden measurement for coal mine management with 3D high resolution compressional and shear velocity seismic inversion

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SUMMARY

High resolution surface seismic surveys can provide useful images of coal bed reflections to depths as shallow as 50 to 100 metres. There is also a need, to gain information of the overburden properties above these depths. This information gap can be addressed by inversion of both the refractions and surface waves ('ground-roll', normally considered to be noise) generated along with reflections as part of the regular survey acquisition. Recent advances in acquisition such as finer spatial sampling, single sensor recording and lower frequency vibroseis sweeps all serve to improve the quality and utility of these data.

In addition to their direct use to infer the petrophysical and hydrodynamic properties of the overburden prior to stripping and mining, the results can be used in reflection seismic imaging. As the compressional velocity (Vp) result is in depth, it can be used for both statics computation and directly as the shallow part of a depth imaging velocity model where reflection-based velocity derivation is poor. The shear velocity (Vs) information can also be used to create a model for subtractive attenuation of the ground-roll for subsequent reflection imaging.

This paper demonstrates how detailed 3D volumes of both Vp and Vs velocities have been co-operatively inverted from diving and surface waves respectively, directly into the depth domain over coal mining leases in Queensland, Australia.

Key words: Seismic inversion, coal mining, shear wave.

INTRODUCTION

Reflection seismic imaging has been used for some time in the management of coal mines in Australia, recently the technique has been applied in 3D with modern technologies and techniques over large areas of known coal resources. This has enabled imaging of the coal seams as shown in Figure 1. By use of dense receiver sampling and dense broadband sources combined with careful image processing and analysis, reliable detailed maps of the coal seams in the range of 50-500 metres depth can be created. However, even with high-resolution reflection seismic techniques a useful image of reflections in the depth range of surface to 50 metres depth is not feasable. Although this very shallow near surface "gap" zone may not contain coal, there is an operational need to understand this near surface zone. It may need stripping for open pit operations or study of groundwater depth and distribution for environmental management planning.

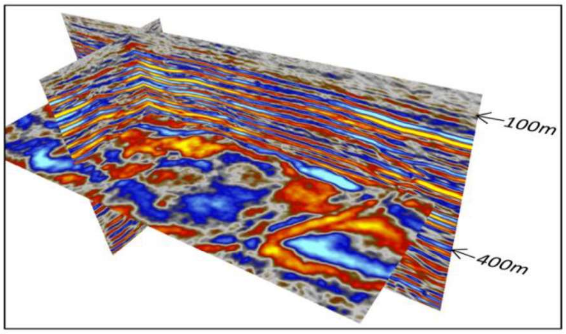


Figure 1. Example depth volume of a modern high resolution reflection 3D coal survey. Note poor reflection image quality above approximately 50metres depth.

Alternative and additional analysis of the data recorded during the reflection seismic survey can yield useful information about the near surface gap. In this paper we will outline and demonstrate methods of seismic inversion to make use of the additional information contained within the seismic recordings. A large portion of the recorded energy consists of surface waves, with multiple propagation modes, propagating in a laterally heterogeneous medium. An example record is provided in figure 2a and 2b.

The surface waves are a form of Rayleigh wave that is commonly referred to as "ground roll noise". Traditionally regarded as coherent noise, it is a signal created by the source and it contains useful information about the shear wave velocity of the near surface, weathered layers and geology. When very low-frequency sources are used, the depth of penetration can reach hundreds of metres.

Previous seismic based studies for this objective, including Suto (2009) and Irwin & Hatherley (1985), reported promising results but recommended further work. These studies used individual 2D multi-channel surface seismic data for 1D surface wave inversion producing point location results. In this study we utilise 3D "production" data collected for the reflection survey and 3D tomographic inversion techniques producing areal depth volumes of both Vp and Vs.

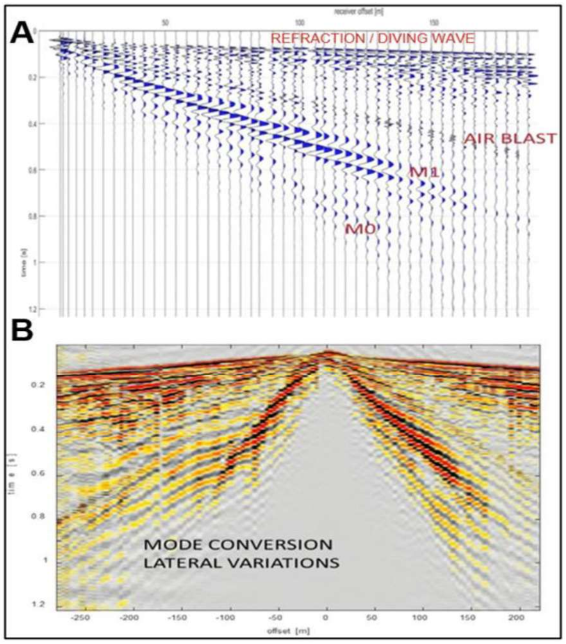


Figure 2. Example 2D shot record of high-resolution single sensor data (4 m sensor spacing), upper panel annotates the wave trains of interest. The lower panel shows considerable lateral variation of the surface waves within 500 metres.

The complexity of the wavefield, as visible in Figure 2B, is associated to the presence of multiple modes with a very dispersive behaviour, sharp lateral velocity variations, mode conversions, and variable spatial absorption.

As these modern data are acquired using point receivers and broadband point sources over an areal zone, they are ideal for the analysis of both refracted compressional and shear waves as they have not been filtered by physical field arrays. Being 3D, they provide large scale multiplicity of measurements over the entire survey zone. The survey geometry has a density that allows an actual 3D analysis of the surface wave wavefield at a very high lateral resolution.

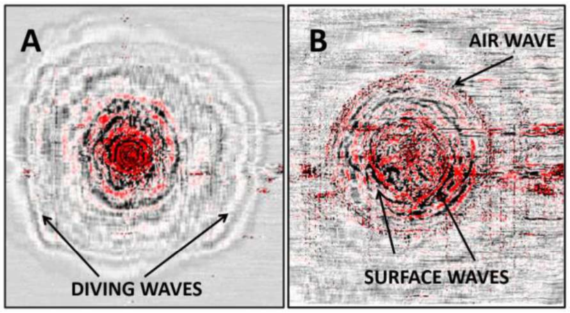


Figure 3. Example 3D gather time slices; A shows the lateral heterogeneity of the refractor (diving wave) velocity, image B, at a later time, shows both the airwave (high frequency circular event) and the dispersive Rayleigh waves (slower than airwave) also describing lateral heterogeneity. This demonstrates the value of 3D acquisition and analysis.

This paper describes the methods used and results achieved from three completed surveys, more are in progress at the time of writing.

METHOD AND RESULTS

Method

The method involves a joint cooperative 3D inversion of the refracted travel time and of the surface wave dispersion. The refraction travel time inversion method generally follows That published by Zhu and McMechan 1989 but in 3D. This non-linear diving wave tomography delivers a 3D Vp model in depth, by matching the picked travel times with those predicted by the velocity model. The surface wave tomography (Strobbia and Foti 2006, Strobbia et. al. 2011) is based on the extraction of the 3D modal dispersion, with a tomographic approach, and then its inversion to obtain the Vs cube also in depth. The cooperative joint inversion approach is implemented without imposing a simultaneous structural or petrophysical constraint but iterating between the two domain inversions, we believe this cooperative approach is novel.

The surface wave analysis is performed with a two-phase workflow. Firstly, the local modal phase velocities are extracted using a local analysis in both source and receiver domains. In these projects the acquisition geometries provide a nearly equivalent spatial sampling, and the integration of the analysis in the common-shot and common-receiver is possible. Following this, a tomographic approach is used to combine all the extracted phases and estimate the wavenumber field with an eikonal phase tomography.

For the refractions, the quality of the first breaks is generally very good, and excellent in the near-offset. An automatic picking workflow is performed: the final picking is obtained iterating ray-tracing and picking, to extract the travel time up to the longest offset. An example of first-breaks picked on the common-shot gathers is provided in Figure 4.

Both inversions were computed and output to a fine spaced grid exactly matching the grid used for the final reflection imaging depth volume, thereby enabling integration of all results in the workstation.

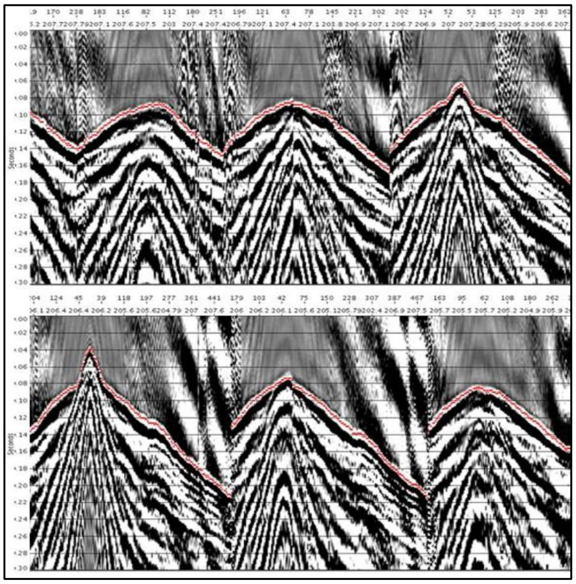
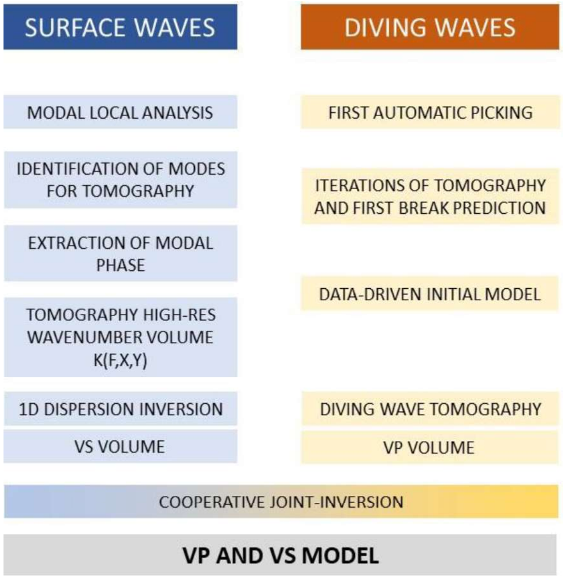


Figure 4. Example of first break picking (red dots) on common shot gathers.

The near-surface modelling workflow can be schematically illustrated as below.



Challenges

The extreme geological complexity of the target zones is evident from the very first steps. The very large dispersion and the sharp lateral velocity variations and mode conversion come directly from the near-surface velocity complexity: large lateral and vertical velocity variations, for both the P and the S wave velocity. The absorption is also particularly high in the shallow, unconsolidated layers.

The latter results in a very rapid spatial decay of the surface wave fundamental mode amplitude, and therefore in its challenging tracking and velocity analysis. The fundamental mode, moreover, is locally largely affected by the very shallow unconsolidated top sediments, with very low shear wave velocity and short wavelength.

The use of higher modes is chosen to simplify the inversion process, it also provides a larger investigation depth especially for older acquisition surveys where the source signal did not extend to very low frequency.

Results

The results of the joint inversion have multiple applications: the models are used in the time imaging workflow to compute statics and in the depth imaging to constrain and resolve the shallow portion of the migration velocity model. The Vp and Vs models also provide structural information, highlighting geological and structural features such as shallow faults. Ultimately, they can be related to petrophysical properties, and could be correlated with practical mining parameters.

The very shallow portion of the velocity model is used to compute model-based statics, computing the vertical travel time to an intermediate datum, therefore compensating for the short-period time perturbations related to the lateral velocity variations in the very shallow near surface. These static corrections are part of the time-imaging workflow.

Then the deeper portion of the near-surface model is embedded into the reflection depth-imaging workflow. The limited offset and fold in the first 50 m of depth makes conventional Common Image Point (CIP) tomography struggle in updating the velocity model. The integrated model from the joint inversion, in its Vp volume, is used as an initial model in the depth imaging model-building workflow. It is then updated via CIP tomography, with prior constraints in the shallow portion. Some large velocity anomalies in the first 50 m depth have been identified and properly accounted for using the integrated near surface velocity model. In these high-resolution coal mining surveys, the first 50 metres of depth is often approximately half way to the first target coal seam, therefore an accurate velocity model of the near surface is essential to reliable depth imaging.

An example of the results of the cooperative inversions for both Vp and Vs is shown in Figure 5.

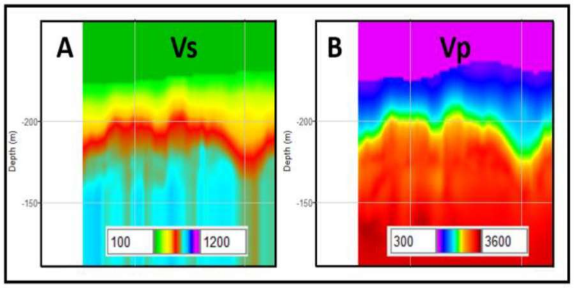


Figure 5. An example 3 km wide section from the two inversion volumes. A is Vs derived from surface waves, B is Vp from diving waves. Note the very slow zone on the right is approximately 50 metres thick. Note the Vs inversion has a shallower depth of investigation limited by the lowest frequency in the source signal.

The interpretation of the models provides useful information and is in general agreement with the reflection data. Locally the depth slices show structural and stratigraphic features. An example of 1 km x 2 km area is shown in Figure 6.

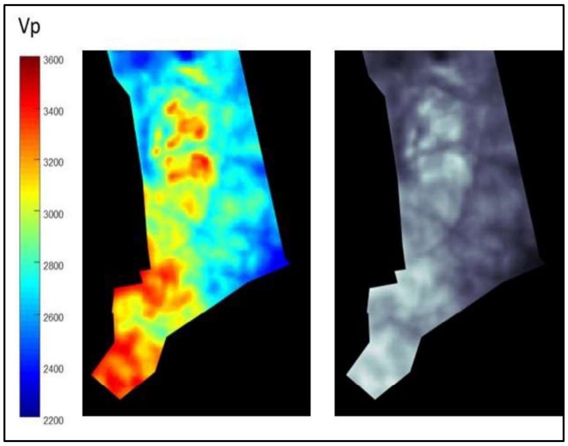


Figure 6. This depth slice at a depth of less than 40 m below the surface and shows the lateral coherency of the velocity and the presence of structures. The right image represents the same slice, in grayscale.

Another example of lineaments identified in the very shallow subsurface is provided in Figure 7.

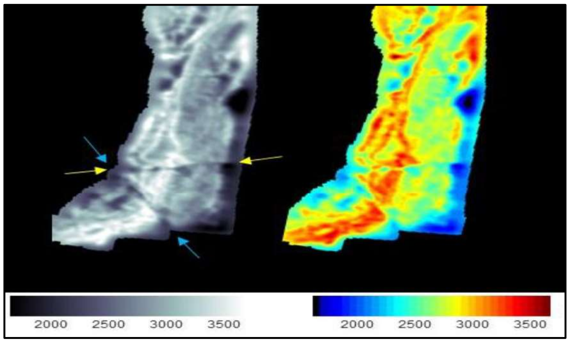


Figure 7. Depth slice at less than 50 m below the surface, showing the geological complexity and structures.

In the overlapping depth zone where there is clear imaging in both the reflection image and the Vp image derived from refraction / diving wave inversion, there is clear agreement in the observed structure. This provides encouragement that the structures observed shallower in the Vp volume are reliable and consistent with geology (Figure 8).

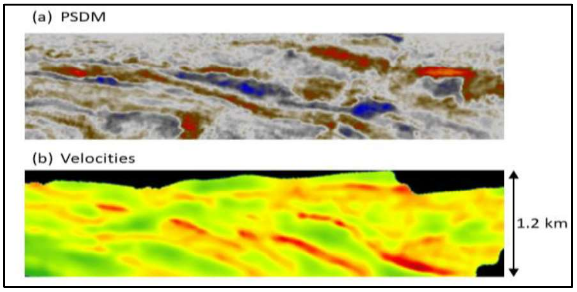


Figure 8. These depth slices at an elevation of 168 m AMSL (approximately 75 m below the surface) show the refraction inversion velocity data (b) and PSDM reflection data (a) have common structure.

The confidence in the shallow Vp velocity cube enabled the extension of fault planes interpreted on the reflection cube in the first 50 metres to within approximately 10 metres below ground level (Figures 9 and 10).

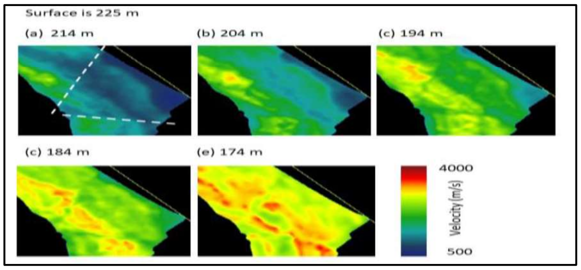


Figure 9. Example depth slices tracking faults in the very near surface. Elevations shown are above mean sea level.

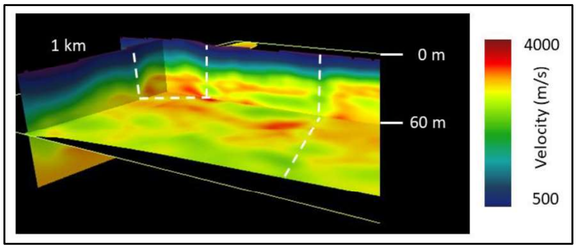


Figure 10. Section view showing faults marked in Figure 9.

Further work

The results confirmed the very high potential of joint refraction and surface wave tomography for mining applications. The vertical sharpness of the model in the very first meters could however be further improved. The necessary regularisation of tomography implies a model smoothness that does not completely leverage the potential depth accuracy of the shallow refraction and surface wave data. A sharp inversion of the near-offset refraction data could provide a better depth estimation of the depth of weathering, an important aspect for planning overburden stripping.

CONCLUSIONS

Modern surface seismic data designed to image reflections from coal layers at 100-500 metres depth can also be used for studies of the overburden / near surface to produce inversion volumes of both compressional and shear velocity. The Shear velocity inversion depth is limited by the lowest possible frequency of the source.

This information can be related to key mine planning objectives such as overburden stripping and groundwater studies. These volumes can also be used to improve the subsurface imaging of seismic reflections particularly in the generation of useful near surface depth-velocity models for reflection-based depth imaging.

These encouraging results are spurring further projects and development of the tools.

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