Evaluation of refraction tomography codes for near-surface applications

Jacob Sheehan and William Doll, Oak Ridge National Laboratory, Oak Ridge, TN*
Wayne Mandell, Army Environmental Center, Aberdeen, MD

Summary

Until recently seismic refraction analysis has been limited to generalized reciprocal, delay-time, or other techniques that require simplifying assumptions such as constant velocity layers and lateral homogeneity within (e.g. Lankston, 1990). The faster and more powerful computers available today have led to the development of various seismic tomography routines. Tomography methods do not make the limited assumptions mentioned above, although each has its own limitations. We compare the performance of three commercially available tomography codes and a delay-time code for representative near-surface models. We use a data set from a site on the Oak Ridge Reservation in East Tennessee (Watson et al., in press, Doll et al., 2002) to represent a typical situation. Results from the synthetic data for each tomography code are compared with results from conventional delay-time analysis. We examine the strengths and weaknesses of these tomographic routines and identify possible artifacts from the inversion.

Introduction

Conventional analyses of seismic refraction data sets make simplifying assumptions about the velocity structure that conflict with observed heterogeneity, lateral discontinuities, and gradients. Relative benefits of some of the conventional approaches are discussed elsewhere (Lankston, 1990, Palmer, 1980). Refraction tomography is designed to resolve velocity gradients and lateral velocity changes enabling it to be applied in settings where delay-time techniques fail, such as areas of compaction, karst, and fault zones. Here, we report on an ongoing comparison involving three commercial refraction tomography codes. Although in concept the three codes should all be able to handle the complications listed above, each has its own theoretical foundation with associated strengths and weaknesses. It is therefore beneficial to carefully study the strengths and weaknesses of each of these codes and of refraction tomography overall. For discussion purposes, the three tomography codes will be called code A, code B, and code C. We have chosen not to reveal the specific code names, as they are all, to some extent, in development, and our assessment may not be valid by the time these preliminary results are published. Our primary intent is to highlight the capabilities of tomographic solutions while warning of some of the pitfalls with present versions of the codes.

The following questions are addressed:

- What are the advantages of tomographic methods over delay-time methods?
- What are the limitations and strengths of each code studied?
- What kind of artifacts or other inaccuracies occur during tomographic analysis?
- How does acquisition geometry affect the results of tomography?

Representative Field Example

The three codes were used to process a data set from the Oak Ridge Reservation in East Tennessee (Watson et al., submitted, Doll et al., 2002). Refraction was used to determine the shallow structure of the site, including the weathered zone and bedrock interface. The data set includes three overlapping collinear lines with one meter spacing, two-meter shot spacing and a total of about 175 shots.

The tomographic results from each code for the field site are shown in Figure 1. Each code shows the same two prevalent horizons. The first is at a depth of about five meters and has a depression near the center of the profile. The second is about 20 meters deep and shows an upwelling in the lower layer directly beneath the depression in the upper layer.

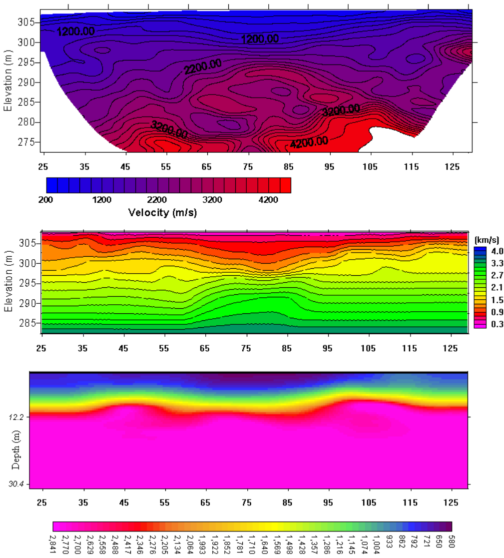

Figure 1: Results for real data from code A(top) code B(middle) and code C (bottom).

The delay-time method used in this study cannot handle more then a few shots at a time, so only the center line was analyzed. Figure 2 shows the delay-time result for this section and Figure 3 shows the same section from the tomography analysis (code A).

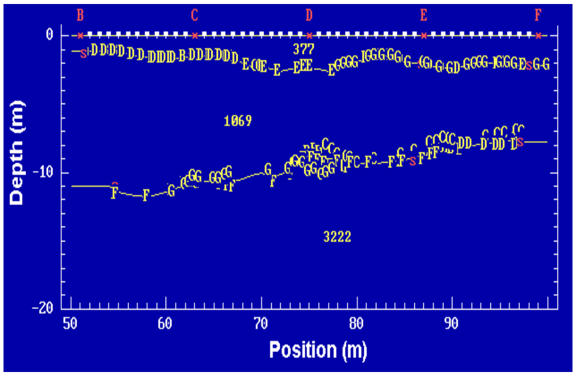

Figure 2: Top: delay-time result for the middle portion of the real field data. Bottom:Tomography results from same line.

Although the delay-time result is similar to the tomography results in some regards, it does not show the same amount of detail, and would most likely lead to an assumption of a simple dipping interface model instead of the depression over upwelling described above.

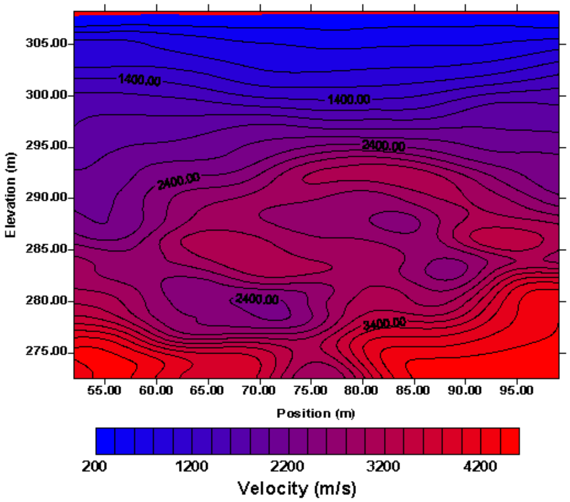

Figure 3: Tomography result for same data as Figure 2.

Synthetic Models

The example shown is typical of many sites where we have worked. To determine which features in the inversion of field data are likely to be real and which are likely to be artifacts of the tomography, a series of synthetic data sets have been created and analyzed. These data sets have also been analyzed with a conventional delay-time code. The synthetic data sets include simple constant velocity layered models, constant velocity layered models with thin layers, gradient models, and models with local heterogeneities. The synthetic travel times for the simple cases are generated using spreadsheet calculations. Commercial finite difference codes are used for the more complicated models (local heterogeneities). In addition to generating synthetics for various subsurface models, synthetics with different acquisition geometries are generated for the same model.

Figure 4 shows a model with a local depression used to generate synthetics and the delay-time inversion results. Five synthetic shots were used, located within the spread and 4 m off each end. Figure 5 shows the tomographic analysis results for the same model.

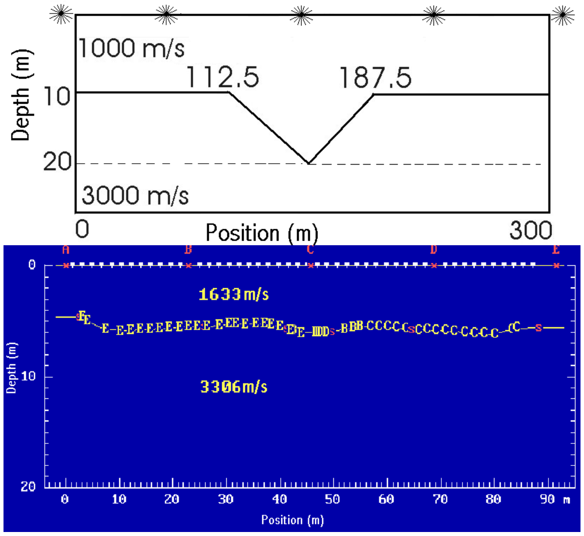

Figure 4: Top: Actual model and shot points, bottom: delay-time inversion of synthetic travel time data.

Code B widens the depression and shows a very significant upwelling below the depression, similar to that in the field data (Figure 1). Code A also shows the upwelling effect seen in code B although it is not as pronounced. Code C does not show this effect, but this could be due to the lack of depth penetration.

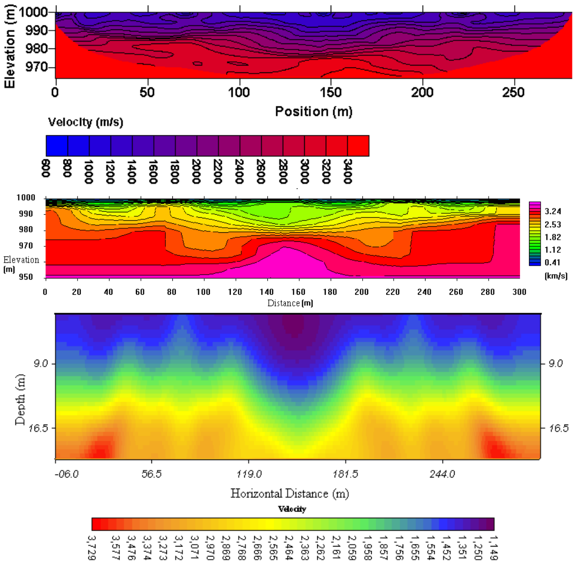

Figure 5: From top to bottom: codes A, B, and C tomography results.

Another model of interest is that of a dipping layer. Figure 6 shows the delay-time results from synthetics generated using a dipping model with layer velocities 1000 m/s over 3000 m/s and the boundary going from 30 meters depth at position zero to 10 meters depth at 300 meters. Five shots with maximum shot offset of 4 meters were used.

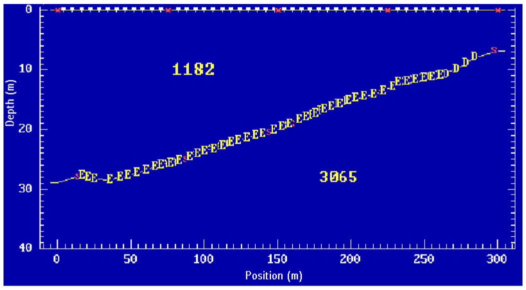

Figure 6: Delay-time inversion of dipping layer model.

Figure 7 shows the tomography results for the same model. Codes A and B both image the dipping layer quite well, but not as well as the delay-time method. Code C assigned higher velocities on the right side of the model instead of bringing the layer closer to the surface. The erroneous velocities can be avoided with very careful velocity constraint, but this is rarely possible without ancillary information (e.g. well logs).

One of the major advantages of tomography is the ability to image gradients. To test this capability the model in Figure 8 was used.

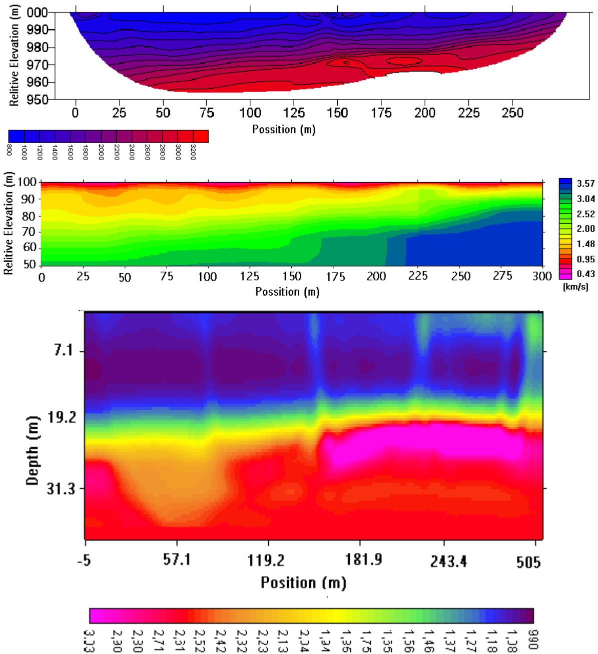

Figure 7: From top to bottom: Tomography restuls from Code A, B, and C respectivly.

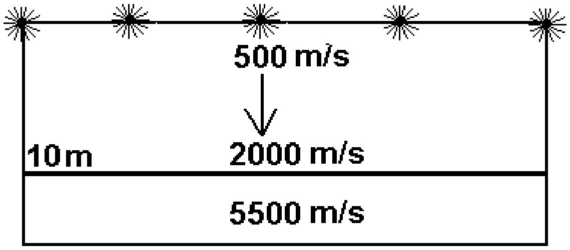

Figure 8: Gradient model over half-space.

Figure 9 shows the tomography results for this model. Both codes model the gradient fairly accurately, although code A does a better job modeling the transition at 10 meters depth. The apparent half-space below 85 meters for code B is an artifact caused by lack of ray coverage.

Gradients make analysis with delay-time methods difficult. In order to use delay-time methods it is necessary to assign first arrivals to a specific refractor. In the case where a gradient is present, this is not possible since the travel-time curves show a constant change in slope, not the sudden change in slope required for layer determination. In addition, since the gradient cannot be modeled directly, a number of constant velocity layers must be assigned to approximate the gradient. This greatly increases the time required for analysis.

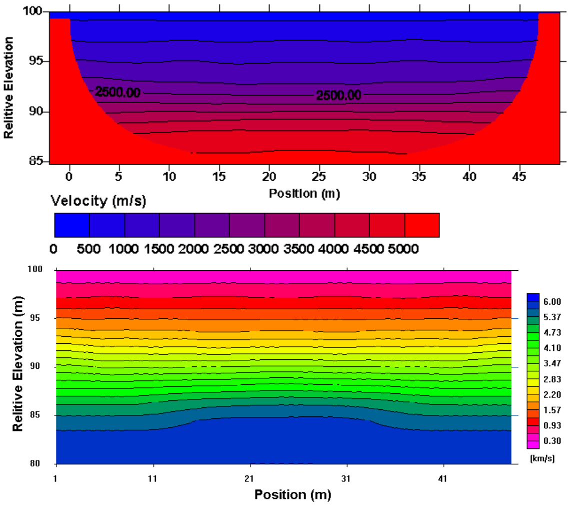

Figure 9: Tomography results from codes A and B for the gradient over half-space model in Figure 8.

Conclusions

In general, the tomographic approach is reliable for realistic synthetic models. These include subsurface models with gradational velocity change and lateral velocity variation. All three codes had difficulty modeling sharp boundaries, modeling them as areas of higher gradient instead of sharp transitions. The delay-time method is able to model the simple non-gradient models better than the tomography.

Each code has its own strengths and weaknesses. Code A handles large data sets well, and gives the most detailed inversion results. It has problems with shot-point related artifacts with small numbers of shots (around five to seven shots). Processing time for 100 shots is around 12 minutes.

Code B does well with few shots but can break down when too many shots are used (>20 or so). The processing time is the longest of the three codes, taking around one hour for 100 shots. The results are significantly less detailed than code A.

Code C does the best in situations of lateral velocity variation and is faster than the other two (a few minutes for 100 shots). The weaknesses of code C include shallower depth penetration and a tendency to assign higher velocities to layers instead of making the interface dip. This can be fixed with carefully selected velocity constraints, but this is rarely possible without ancillary information (e.g. well logs). Table 1 shows the ranking of each code for the different kinds of models studied:

	Program A	Program B	Program C	delay-time
Horizontal	2	3	4	1
Dipping	2	2	4	1
Gradients	1	1	3	4
Localized	2	2	1	4

Table 1: Ranking chart for studied codes.

As Table 1 shows, no single code works best for all models that we tested. Results from the tomography codes must be treated cautiously, but are generally better than conventional methods when the underlying assumptions of the conventional codes are violated.

References

Dobrin, M.B., 1976, Introduction to geophysical prospecting, fourth ed.: New York, McGraw-Hill.

Doll W.E., T.J. Gamey, D.B. Watson, and P.M. Jardine. 2002. *Geophysical Profiling In Support Of A Nitrate And Uranium Groundwater Remediation Study, Extended Abstracts. 2002 Symposium on the Application of Geophysics to Engineering and Environmental Problems, Las Vegas, NV.* Feb. 10-14, 2002, 10p

Lankston, R.W. *High-Resolution Refraction Seismic Data Acquisition and Interpretation,* Geotechnical and Environmental Geophysics, Society of Exploration Geophysics. pp 45-73

Palmer, D., 1980 The Generalized Reciprocal Method of Seismic Refraction Interpretation: Tulsa, Society of Exploration Geophysicists.

Watson, D.B. Doll, W.E., Gamey, T.J., Sheehan, J.R. and Jardine, P.M. *Use Of Geophysical Profiling To Guide Groundwater Remediation Studies,* submitted to *Groundwater.*

Acknowledgements

We would like to thank the vendors of two of the codes that were tested for providing their codes to us at no cost for these tests, and for prompt answers to our questions and modifications that have simplified the comparisons. We gratefully acknowledge the Army Environmental Center for funding this work. Oak Ridge National Laboratory is managed by UT-Battelle, LLC for the U. S. Department of Energy under contract DE-AC05-00OR22725. The submitted manuscript has been authored by a contractor of the U. S. Government. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.