Validating vertical velocity gradients in near-surface refraction seismology

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SUMMARY

Wavepath eikonal traveltime (WET) refraction tomograms are generated with the generalised reciprocal method (GRM), a novel medium resolution common offset gather (COG) implementation of the GRM, both using uniform velocities and vertical velocity gradients, and the low resolution default starting model consisting of smooth vertical velocity gradients. All tomograms have comparable misfit errors, which illustrates the ubiquity of non-uniqueness and the necessity for validating all starting models.

Nevertheless, the use of even the maximum vertical velocity gradients in the weathered region does not produce any improvement in the spatial resolution of the seismic velocities in the sub-weathered region with either the default or the COG GRM starting models. It is concluded that if a low resolution starting model is used, then the most likely outcome will be a low resolution WET tomogram, irrespective of whether or not vertical velocity gradients are employed.

Vertical velocity gradients can be represented as part of a continuum of seismic velocities in the weathered layer, which range from uniform to hyperbolic velocities, and which are consistent with the traveltime data. Acceptable models employ seismic velocities in the weathered and sub-weathered regions computed with the same XY value. The optimum XY value is representative of uniform seismic velocities, whereas the maximum XY value, which is the average cross-over distance, is representative of default and hyperbolic velocities. Intermediate XY values indicate more moderate vertical velocity gradients and/or undetected layers.

Key words: GRM, common offset gathers, non-uniqueness, near-surface refraction seismology, tomography, vertical velocity gradients.

INTRODUCTION

Are vertical velocity gradients ubiquitous?

Refraction tomography is an example of model-based inversion, in which a starting model is systematically updated until the computed response is similar to the data. A common expectation is that tomography will significantly improve the resolution of the model. A commonly used default starting model consists of smooth vertical velocity gradients.

Nevertheless, the use of vertical velocity gradients can often be inappropriate. For example, saturated unconsolidated sediments, which are frequently recognized as an abrupt change in the seismic velocities at the water table, commonly exhibit reasonably uniform seismic velocities of approximately 1750 m/s, with any increase usually being as the one sixth power of depth ($Z^{1/6}$), and ~1 m/s per metre.

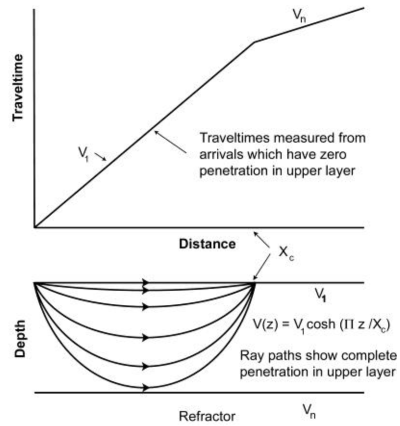

Figure 1: Schematic traveltime graph and ray paths for the hyperbolic velocity function in the upper layer.

Furthermore, vertical velocity gradients can be readily fitted to virtually any set of traveltime graphs, even where uniform seismic velocities are more appropriate. The hyperbolic velocity function is the maximum vertical velocity gradient which is consistent with linear traveltime graphs and uniform seismic velocities. Figure 1 demonstrates complete ray path coverage within the upper layer with the hyperbolic velocity function even though there are no first arrival traveltimes which represent ray paths with penetration within the upper layer. In this study, the gradients exceed 10 m/s per metre.

This study demonstrates that the wavepath eikonal traveltime (WET) refraction tomograms, generated with the default starting model consisting of smooth vertical velocity gradients have misfit errors which are comparable to those for a variety of WET tomograms generated with the generalised reciprocal method (GRM) (Palmer, 1980) and a novel common offset gather (COG) implementation of the GRM (Palmer, 2012), using both uniform velocities and vertical velocity gradients. These results challenge the usefulness of simplistic comparisons of misfit errors for differentiating acceptable tomograms. They illustrate the ubiquity of non-uniqueness and in turn, the necessity for explicitly validating the starting model, especially the assumption of vertical velocity gradients, which frequently are not geologically reasonable.

The Wirrinya data

The data used in this study are a subset of the 17 km Wirrinya traverse 99WR-HR1 (Palmer, 2012). This analysis focuses on a 2 km interval between stations 1450 and 1650 recorded over Tertiary alluvium, in which only modest vertical velocity gradients might be anticipated.

GRM STARTING MODELS

GRM time model

Figure 2 presents the GRM time model for the base of the weathering for a range of XY values. Figure 2 supports the common observation that the resolution of the time model is essentially independent of the XY spacing for most near-surface investigations and that any reasonable XY spacing, such as zero, is often sufficiently accurate.

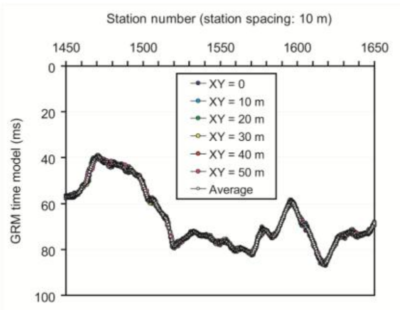

Figure 2: GRM time model for a range of XY values.

GRM seismic velocities

Detailed seismic velocities are computed with a multi-chord algorithm. This procedure achieves detailed spatially varying seismic velocities, while at the same time, it accommodates the ill-posedness of the process.

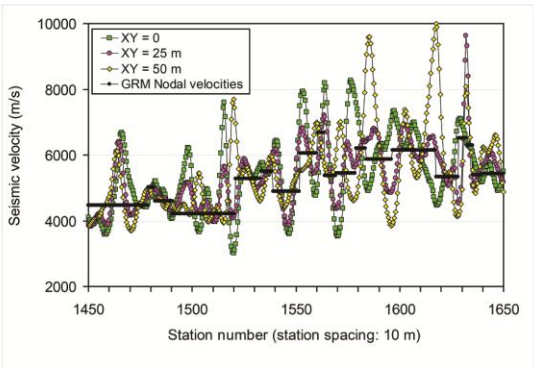

Figure 3: Comparison of the GRM seismic velocities computed with XY values of 25 ± 25 m with the GRM nodal seismic velocities.

In addition, another seismic velocity, termed the "nodal velocity" is computed. This velocity is the average seismic velocity between those stations where the refractor velocity analysis function has the same value for all XY values. The nodal velocities do not require interpretation skills comparable to those necessary for the determination of the optimum XY value of ~25 m. The spatial variations in the seismic velocities in the sub-weathered region computed with XY values of 25 ± 25 m, are consistent with the nodal velocities, as shown in Figure 3.

COG GRM STARTING MODELS

COG GRM time model

The common offset gather (COG) implementation of the GRM is described in some detail in Palmer (2012). The COG GRM time model algorithm is essentially the same as the common reciprocal method version of the GRM. The difference is that *only a single value* is computed with each source separation (ΔVP) for the receiver midway between the two sources.

The COG GRM gathers are generated by implementing the algorithm with a systematic increase in the source-to-source distance ΔVP, in multiples of twice the station spacing, with the objective of progressively delineating increasingly deeper interfaces. Figure 4 presents the COG GRM time model for the source spacing from the minimum of 20 m to 600 m, together with the average for the source spacing of 300 m to the maximum of 1200 m.

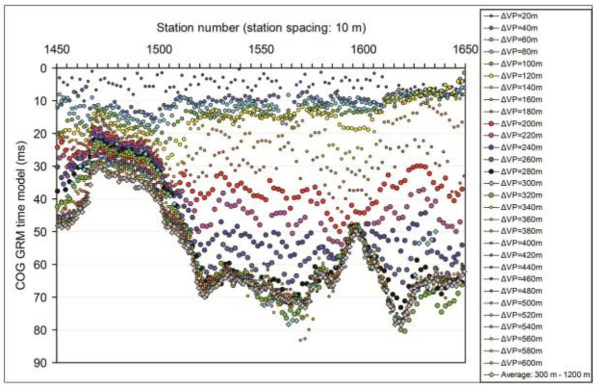

Figure 4: The GRM common offset time model gather.

Time models for the base of the surface layer of approximately 15 ms near station 1450 to approximately 7.5 ms near station 1650 are indicated with the source separations of 40 m to 120 m. With increases in the source spacing, the time models are generated with traveltimes which are representative of disparate layers, and therefore, they are meaningless. Eventually, the time models employ traveltimes from the same layer, and they then cluster about an average value for a range of source separations. Figure 4 shows that the minimum value is 280 – 300 m. The source separation of 300 m will be taken as the minimum for defining the base of the weathering.

The source separation of 300 m is approximately twice the cross-over distance, which marks the transition of traveltimes from the weathered region to those from the sub-weathered region. The significance of the cross-over distance of 150 m is that it represents the maximum possible optimum XY value, which in turn, corresponds with the maximum vertical velocity gradient, namely the hyperbolic velocity function as shown in Figure 1. For completeness, GRM WET tomograms are computed using a time model and seismic velocities computed with an XY value of 150 m.

COG GRM seismic velocities

The COG GRM refractor velocity analysis algorithm employs a novel four-term modification of the standard GRM velocity analysis algorithm. As with the COG GRM time model algorithm, *only a single value* is computed with each source separation for the receiver at G.

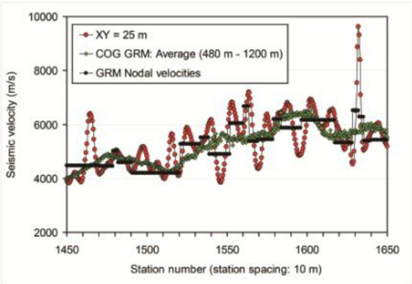

Figure 5: Comparison of the GRM and the common offset GRM seismic velocities.

Figure 5 compares the seismic velocities in the sub-weathered region computed with the GRM and the COG GRM. The average wavelength of the GRM seismic velocities is ~125 m, whereas that for the COG GRM seismic velocities is ~500 m.

WET TOMOGRAPHY

Default tomograms – smooth vertical velocity gradients

Figure 6 presents the smooth vertical velocity starting model, and the WET tomograms for 5 and 20 iterations, the latter being the default. Both tomograms show the same general changes in depth indicated in the GRM and COG GRM time models.

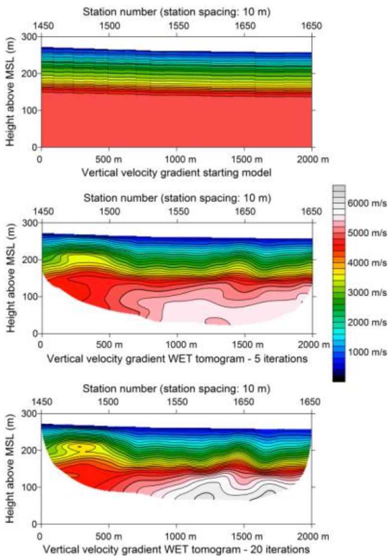

Figure 6: Starting model and WET tomograms for the smooth vertical velocity default.

It is difficult to identify unambiguously any region which might correspond with the base of the weathering. A common rule of thumb has been to select the region where the contours of the seismic velocities converge, that is, where they show a larger vertical gradient. However, that is not possible in Figure 6 because the contours are essentially equally spaced up to a seismic velocity of ~4000 m/s in the vicinity of station 1500, and 5000 m/s elsewhere.

The RMS misfit errors are presented in Figure 7.

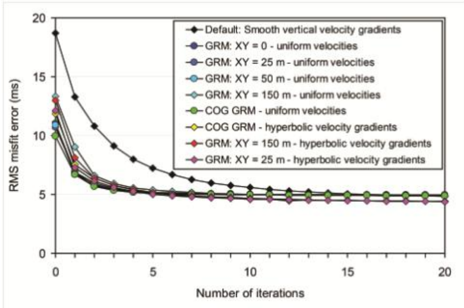

Figure 7: Misfit errors as a function of the number of iterations for all WET tomograms.

COG GRM and GRM tomograms

Figure 8 presents the starting model and the WET tomograms after 1 and 2 iterations for the COG GRM model employing uniform seismic velocities in the weathered region. The single application of tomography has largely cosmetically smoothed most of the high frequency artefacts generated by the gridding operation.

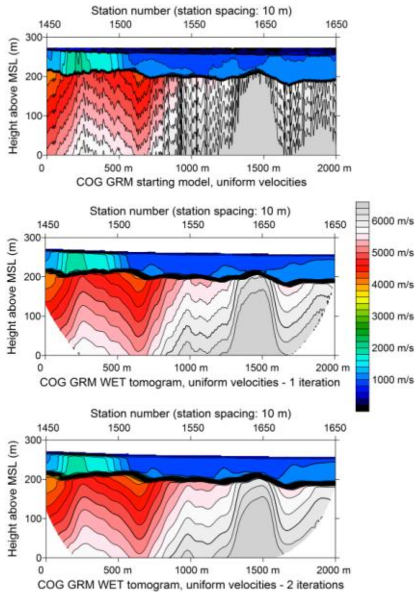

Figure 8: Starting model and WET tomograms after 1 and 2 iterations for the COG GRM starting model with uniform seismic velocities in the weathered layer.

It can be reasoned that accuracy, that is, the model, is more important than precision, that is, any measure of the misfit errors. Nevertheless, it is recognised that this may not necessarily be a widely held position. For that reason, the various GRM tomograms generated after 5 iterations are presented because the misfit errors have stabilised and are comparable with those achieved after many more iterations.

Figure 9 presents the GRM WET tomograms for XY values of 25 ± 25 m after five applications of refraction tomography.

These tomograms represent the maximum resolution which might be employed for detailed interpretation with substantially expanded vertical and horizontal scales.

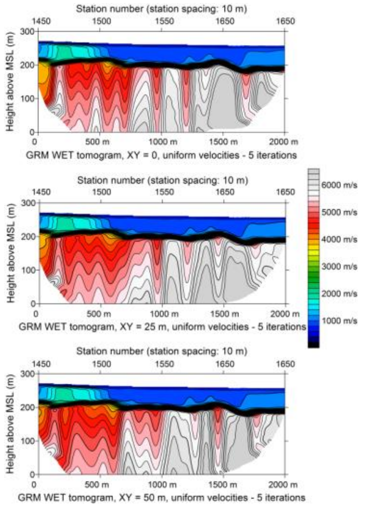

Figure 9: WET tomograms after 5 iterations for the GRM starting models computed with XY values of 25 ± 25 m with uniform seismic velocities in the weathered layer.

Figure 10 summarises the three most acceptable models. The COG GRM WET tomogram, which employs uniform seismic velocities in the weathered layer, represents a medium resolution model, which would be suitable for statics corrections for seismic reflection data processing. The GRM WET tomogram, which employs uniform seismic velocities and an XY value of 25 m, is considered to be the most probable and would be suitable for most detailed geotechnical investigations. The third GRM WET tomogram, which employs the hyperbolic velocity function and an XY value of 150 m, is the most appropriate where vertical velocity gradients are considered to be applicable.

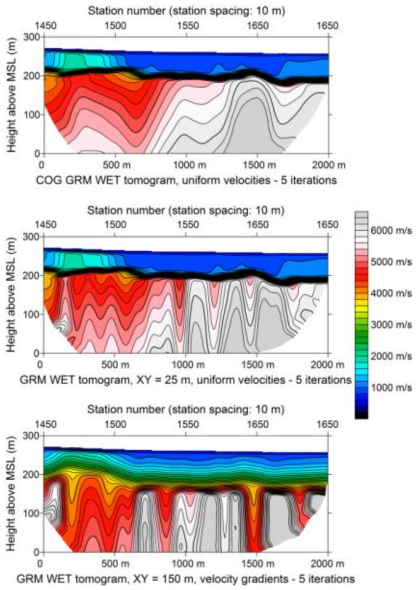

Figure 10: Three WET tomograms, which represent the most probable models, after 5 iterations.

CONCLUSIONS

Most geologically reasonable velocity gradients in clastic sediments are quite modest. As a result, the recognition of any vertical velocity gradients in the near-surface region with curved traveltime graphs is usually ambiguous. Nevertheless, it is possible to fit velocity gradients with default starting models and with hyperbolic velocity functions, which are more than an order of magnitude larger than most geologically reasonable values.

However, the use of even the maximum vertical velocity gradients in the weathered region does not result in any improvement in the spatial resolution of the seismic velocities in the sub-weathered region. It can be concluded that if a low resolution starting model is used, then the most likely outcome will be a low resolution tomogram, irrespective of whether or not vertical velocity gradients are employed.

Vertical velocity gradients represent one component of a continuum of seismic velocities in the weathered layer which range from uniform velocities to hyperbolic velocities, and which are consistent with the traveltime data. In this study, the optimum XY value of 25 m is representative of uniform seismic velocities, whereas the maximum XY value of 150 m, which is the average cross-over distance, is representative of the maximum vertical velocity gradient. Intermediate XY values are indicative of more moderate velocity gradients and/or undetected layers. The GRM average vertical velocity, through the XY distance, provides a more precise measure of the average velocity in the weathered layer than is possible with WET tomography using the direct traveltimes in the weathered layer.

Valid starting models are computed with seismic velocities in the weathered and sub-weathered regions which employ the same XY value. In this study, the WET tomogram generated with the optimum XY value of 25 m is considered to be the most likely. However, the WET tomogram computed with a 150 m XY value is presented as an alternative model, should vertical velocity gradients be considered applicable. Furthermore, models generated with the common reciprocal method are not considered to be valid, even though they have acceptable misfit errors, because they imply a zero seismic velocity in the weathered layer.

A major conclusion of this study is that WET tomography is largely a smoothing operation which does not improve the spatial resolution of either medium resolution or detailed starting models. In those applications where detailed spatial resolution is an important consideration, then it is necessary to employ starting models with comparable appropriate resolution, such as those generated with the GRM.

REFERENCES

Palmer, D., 1980, The generalized reciprocal method of seismic refraction interpretation. SEG, 104p.

Palmer, D., 2012, Generating starting models for seismic refraction tomography with common offset stacks: *Exploration Geophysics* **43**, 242-254.