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Letting the Data Drive the Initial Model Building for Refraction Tomography

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Summary

Near-surface characterization is an important part of the land seismic data processing workflow. Conventional approaches rely on refracted waves and estimate the compressional velocity models from the tomography of the first-break traveltimes (Glushchenko et al., 2012, Speziali et al., 2014). Like many geophysical inverse problems refraction tomography suffers from nonuniqueness (Kanlı, 2009, Mantovani et al. 2013) and must be studied to determine what type of apriori information is necessary to find a realistic solution (Ivanov et al., 2005). The set of model parameters that are inferred by solving a nonunique inverse problem is heavily dependent on the initial distribution of the model parameters (Noori et al., 2012). In other words, when dealing with nonunique problems the initial model heavily influences the final model that can be obtained.
For this reason, while executing a geophysical data processing workflow that relies on the solution of a non-unique inverse problem, one should make certain that the solution obtained is stable with respect to the choice of the initial model. This requires a thorough exploration of the starting models, which is not always feasible given the increasing amount of geophysical data collected during a survey and the fact that geophysical data processing projects are subject to time and resources constraints. This is particularly true for modern 3D land seismic surveys where refraction tomography is routinely used to characterize the near-surface and to build the shallow part of the velocity model in depth migration workflows.
In this work, we propose a method that derives the initial 3D velocity model for the tomography workflow directly from the first-break picks, thus limiting the amount of subjectivity that influences the initial model definition (Osypov, 2001). The method recovers a one-dimensional (1D) distribution of the velocity that can mode the first arrivals in the offset-time domain. This technique computes the 1D approximation for each gather of first-break picks and can operate in the shot or in the receiver domain. The resulting 1D velocity profiles are up-scaled and regularized to obtain the 3D velocity field used as a starting model for the 3D refraction tomography workflow. We demonstrate the effectiveness of the technique by its application on a synthetic, but realistic, 3D example. We also showcase the technique on a 2D survey from north Africa, where the 1D modeling was successfully applied as initial model building for a 3D diving wave tomography.

Theory and method

In the presence of a 1D velocity distribution made by layers extending indefinitely in the horizontal direction and with finite thickness (Figure 1a), it is possible to compute the time of the refracted arrival from the *n*-th layer as (Sheriff and Geldart, 1982):

$$t_n = \frac{x}{v_n} + \sum_{i=1}^{n-1} \frac{2h_i \cos(\vartheta_i)}{v_i}.$$

In the equation above, x is the source-receiver offset, v_n is the velocity of the *n*-th layer, and v_i and h_i indicate, respectively, the velocity and the thickness of the *i*-th layer. With reference to figure 1a, the angle ϑ_i is computed as if it was the critical angle between the *i*-th layer and the infinite half-space with velocity v_n. Hence, as schematically depicted in Figure 1b, a 1D velocity profile composed by horizontal layers extending indefinitely leads to refracted arrivals laying on linear segments. The slope of the segments is the slowness of the layer that generated the refracted arrival, while the intercept time T_i is a proxy for the thickness of the (*i*-1)-th layer. Given the slopes of the linear segments and the intercept times, it is possible to derive the thickness of the (*n*-1)-th layer in an iterative fashion from the shallower layer down to the deepest one using the following formulae:

$$h_{n-1} = \frac{T_n - \tau_n}{v_n}, \text{with } \tau_n = \sum_{i=1}^{n-1} \frac{2h_i \cos(\vartheta_i)}{v_i}.$$

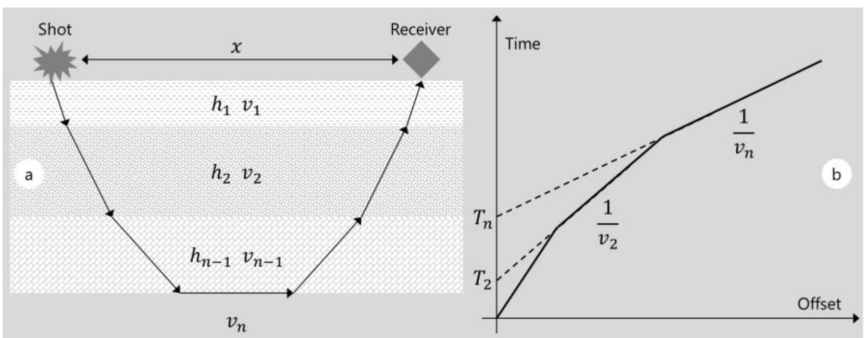

Figure 1. *Refracted arrivals for a 1D horizontally layered velocity model (a). In case of a 1D horizontally layered model, the arrivals lay on linear segments in the offset-time space.*

The method we propose uses as input the first-break picks belonging to a single shot or receiver gather. The offset axis is divided into bins and for each bin a linear regression is carried out providing an estimate of the slope and the intercept time. When the analysis of the shot or the receiver gather is completed, the thickness of each layer is derived according to the previous formulae. The 1D model obtained consists of N thickness values and $N + 1$ velocity values; the last value of velocity is assumed to be the velocity of a half-space extending to infinity.

After having obtained a 1D velocity model for each shot or receiver gather, these are up-scaled to the 3D grid defining the velocity model (i.e., target grid). Each 1D model is placed into the 3D space according to the coordinates of the shot or receiver defining the gather from which the 1D model was derived.

Results and examples

To test the capabilities and the effectiveness of the technique discussed above, we created a 3D synthetic data set emulating a land seismic survey acquired with a cross-spread geometry over an area covering approximately 450 km^2. The source lines are oriented west-east with source line and shot intervals equal to 100 m. The receiver lines are laid out along the north-south direction with an interval of 200 m and a receiver interval of 25 m.

The total number of shots is around 34,000 with each shot having a maximum offset of 2 km in each direction, leading to approximately 104 million traces. The topography simulates dunes or foothills and has a maximum excursion of 240 m. Together with the topographic variability, the

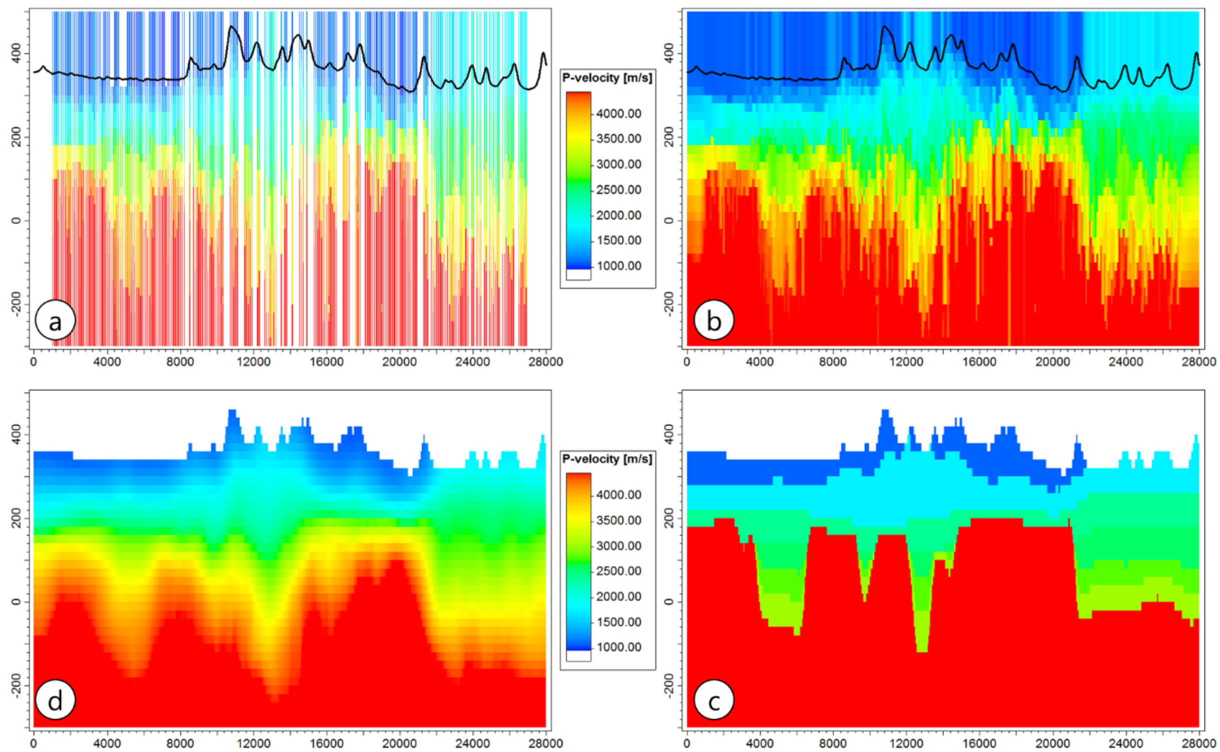

Figure 2. *Results of applying our methodology on a synthetic data set. In (a), the result of up-scaling the 1D models into the 3D grid (white means no data). The white gaps in (a) are filled by the minimum curvature interpolation and the result is shown in (b). The black line in (a) and (b) represents the topography. In (c), the synthetic velocity section that generated the first-break picks, while in (d), there is a smoothed version of the raw result shown in (b). All the units of distance are meters.*

synthetic model also includes lateral changes in both the shallow and deep portions of the section where the dominant refractor is not continuous along the horizontal direction.

The technique was applied to the synthetic data set in the shot domain. The results obtained for a single north-south section are presented in figure 2. Figure 2a shows the results of up-scaling the layered 1D models onto the 3D grid. The color indicates the velocity values of the 1D models while the white spaces between the columns represent the gaps left by the up-scaling process. The gaps are filled by the minimum curvature interpolation process. The raw interpolated model is shown in figure 2b while the corresponding section of the true synthetic velocity model is depicted in figure 2c.

The section in figure 2b shows abrupt lateral variations of the velocity due to the 1D assumption that was made when estimating the vertical velocity profiles from the shot gathers. When comparing this section with the corresponding section of the synthetic velocity model, we can see how the main traits of the velocity field are nicely captured. To remove the artifacts created by the up-scaling process we applied a smoothing to the raw model and obtained the result shown in figure 2d.

Following the validation on the synthetic dataset, the algorithm was applied on a real dataset from a 2D survey in north Africa. The survey covers a vast area (approx. 14500 km^2), characterized by significant variations in the near surface geology and no borehole information was available for the velocity model building.

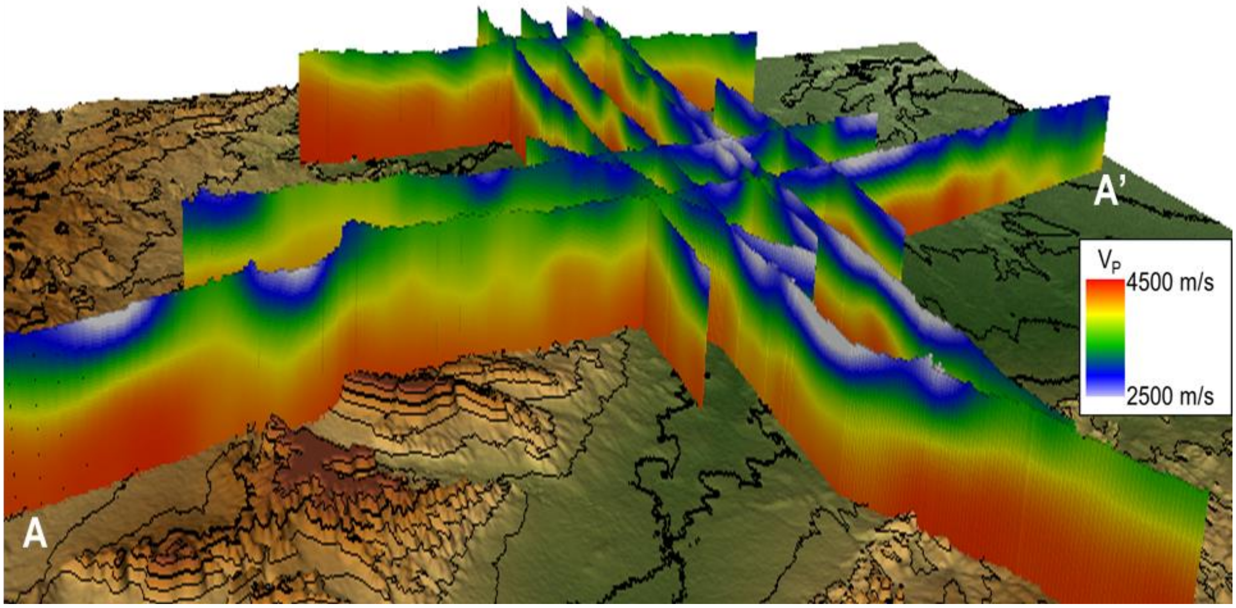

***Figure 3**. Result of the data-driven approach on a 2D dataset from north Africa. The distance from A to to A' is approximately 100 km, and model depth is 800m. The 1D modelling successfully captures the long wavelength features of the near surface, in excellent agreement with the expected geology.*

The data driven approach successfully overcame those challenges, providing a velocity model in excellent agreement with the expected geology, paving the way for a quick convergence of the forthcoming diving wave tomography (Figure 3).

Conclusions

We presented an automated data-driven technique to estimate the initial model for the refraction tomography workflow. The technique derives a 1D velocity profile for each gather – in shot or receiver domain – using refracted arrivals and then up-scales and interpolates the collection of 1D velocity profiles into the three-dimensional velocity grid.

The method was applied on a synthetic data set simulating an onshore 3D seismic acquisition over an area with large lateral velocity variations in the near surface. The results prove that our method, despite starting from a very rough 1D assumption, can recover the main lateral and vertical variations of the velocity field.

The method was also successfully applied to a real dataset acquired in North Africa to create the starting model for a 3D diving wave tomography workflow.

As a final remark, the method presented for two onshore scenarios applies also to a marine or to an ocean-bottom cable/ocean-bottom node acquisition. Furthermore, the velocity model derived from the refracted arrivals can be used as a starting point also for a full-waveform inversion workflow.

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