ON CORRECTING FOR SEISMIC TRAVEL TIME ANOMALIES CAUSED BY NEAR-SURFACE ROCK LAYERS

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ABSTRACT

In this paper, we give a brief overview of the problem of modeling the near-surface rock layers, which are often responsible for causing significant distortions of the travel times of seismic waves used for oil and gas exploration. The modeling scheme is a nonlinear inverse problem. In addition to the theoretical overview, we show practical results from a west Texas seismic survey obtained using the popular generalized linear inversion method for solving the modeling problem.

1. INTRODUCTION

The main goal of the seismic method, as applied to oil and gas exploration, is to deduce certain properties of the subsurface rock formations based on measuring travel times associated with the propagation of sound waves in the subsurface. In its most general form, this is a large and complicated inverse problem. There are numerous factors that contribute to the complexity of this problem, and in this paper we will be concerned with one such factor: anomalous travel time variations caused by wave propagation in the unconsolidated near-surface rock layers.

The common approach for dealing with this problem goes by the name "static corrections" in the seismic data processing literature. In this approach, each seismic trace recorded by a receiver is shifted in time by an amount that corrects for the distortion caused by the near-surface layers. This correction is arrived at by first modeling those layers (i.e., estimating the velocity and thickness functions associated with them), and then replacing the computed travel time within this model by the travel time that the wave would have taken in a more homogeneous and consolidated layer. For a general review of static corrections, see, for example, Marsden (1993).

The main challenge in static corrections often has to do with the problem of getting an accurate model of the near-surface layers. The modeling scheme is, itself, an inverse problem. The travel times used in this particular inversion are typically picked on the seismogram and are often associated either with a certain strong reflecting rock interface or with energy that critically refracted at (and traveled along) the bases of the near-surface layers. When the anomalies have large amplitudes and large spatial wavelengths, inverting the travel times associated with *refractions* at the bases of the near-surface layers typically leads to more accurate results. In that case, the static corrections problem goes by the name "refraction static corrections."

In this paper, we consider the modeling problem associated with refraction static corrections. We begin by discussing the refraction model in Section 2, and then consider the associated inversion problem in Section 3. A particular example involving the use of the generalized linear inversion method is given in Section 4. Finally, Conclusions are drawn in Section 5.

2. THE REFRACTION MODEL

We begin the discussion with the very simple model shown in Figure 1, which consists of a source S, a receiver R (both located at or near the surface of the earth), and N geologic layers. The source-to-receiver distance is denoted h. Now, associate with each layer ℓ a constant velocity v_ℓ and a constant thickness d_ℓ. Furthermore, assume that the velocity increases with depth; i.e., $v_1 < v_2 < \ldots < v_N$. Next, for any two layers i and j such that $i < j$, let θ_{ij} denote the angle defined by

$$\sin \theta_{ij} = \frac{v_i}{v_j} \; . \tag{1}$$

Then, for any $\ell \in \{2, \ldots, N\}$, the travel time t_ℓ associated with the ray that critically refracted at the top of layer ℓ can be computed using Snell's law (e.g., see Dobrin (1976)), and is given by

$$t_\ell = 2\left(\sum_{k=1}^{\ell-1} \frac{d_k \cos\theta_{k\ell}}{v_k}\right) + \frac{h}{v_\ell} \ . \tag{2}$$

For a given source/receiver pair, except when h is very small, the first seismic waves to arrive at and be recorded by the receiver are those associated with one of the t_ℓ's above, for some $\ell \in \{2, \ldots, N\}$. This first arrival, call it $t_{\min}$, is usually "picked" (i.e., measured) on the seismogram, and is thus given by

$$t_{\min} = \min_{\ell \in \{2,\ldots,N\}} t_\ell \tag{3}$$

When Equation (3) is written for every source/receiver pair for which a first arrival measurement is available, one obtains a system of nonlinear equations relating the measured travel times ($t_{\min}$'s) to the model parameters ($v_1, \ldots v_N$, and $d_1, \ldots, d_{N-1}$).

3. THE INVERSION PROBLEM

In its simplest form, the inversion problem under consideration involves computing the model parameters (velocities and thicknesses) given the first arrival times. It is clear, however, that if the true earth were as simple as Figure 1 suggests, there would be no near-surface-related wave distortions. In reality, the velocity and thickness functions associated with each layer are spatially varying, so that one now writes $v_\ell(x, y)$ and $d_\ell(x, y)$ to denote these functions. As long as this variation is kept reasonably small (e.g., gently dipping layers with fairly smooth velocity functions), the equations given in in the previous section still hold with only minor modifications.

To get a feeling for the size of the problem being faced in practice, a typical land 3-dimensional seismic survey might yield a few million first arrival time measurements, while the number of unknowns (after discritizing $v_\ell(x, y)$ and $d_\ell(x, y)$ for each layer ℓ) may run into a few thousands. A number of approaches have been proposed over the last few years to attack this rather large nonlinear inversion problem. One such approach, which has gained wide acceptance in industry in recent years, is the Generalized Linear Inversion approach, which was proposed for solving this problem by Hampson and Russell (1984). This approach is summarized in the following algorithm:

1. Choose an initial guess of the near-surface geological model.
2. Compute first arrival times by ray tracing in the current model.
3. Compare the computed first arrival times with the measured first arrival times.
4. If the results of the comparison are satisfactory, stop. Otherwise, modify the model, and go to step (2).

In practice, the model updating in step (4) above is carried out one layer per iteration, and is usually based on a linearized version of Equation (2) derived using a Taylor series expansion.

Once a satisfactory near-surface model is obtained, it is used to compensate for the associated travel time anomalies in the following manner. Recall, first, that the layers associated with oil and gas exploration are typically much deeper than the near-surface layers modeled here. Waves associated with reflections from those deep layers tend to travel nearly vertically when they are close to the surface. For any given location (x, y) on the surface, the travel time associated with a ray traveling vertically through the computed model is given by

$$T_m(x, y) = \sum_{j=1}^{N-1} \frac{d_j(x, y)}{v_j(x, y)} \ . \tag{4}$$

On the other hand, for the same location, the travel time associated with a ray traveling vertically through an ideal homogeneous layer with velocity v_i[1] is given by

$$T_i(x, y) = \frac{1}{v_i} \sum_{j=1}^{N-1} d_j(x, y) \ . \tag{5}$$

Hence, for any given source at location (x_s, y_s), the time shift needed to replace the near-surface layers by the homogeneous ideal layer is given by

$$T_s(x_s, y_s) = T_i(x_s, y_s) - T_m(x_s, y_s) \ . \tag{6}$$

For a receiver at location (x_r, y_r), a similar computation is made, but the time shift is now denoted $T_r(x_r, y_r)$ instead of $T_s(x_s, y_s)$. Finally, since any recorded seismic trace is associated with one source and one receiver, each such trace is shifted by the amount

$$T = T_s(x_s, y_s) + T_r(x_r, y_r) \ . \tag{7}$$

The shifts given in Equation (7) are known as refraction static corrections.

Slightly more complicated versions of Equations (4-7) are often used in practice to account for the depth of the source (e.g., in the case of a dynamite source), and to allow for a user-specified processing datum, essentially moving the sources and the receivers to any desired surface.

[1] Usually v_i is chosen such that $v_i \approx v_N$.

4. A PRACTICAL EXAMPLE

The algorithm given above is implemented in Hampson-Russell, Inc.'s software package GLI3D (Reference [3]). We used this package to model the near-surface rock layers in the Lockridge-Waha Permian basin in west Texas.

A schematic diagram of an east-west geologic cross-section of the near-surface layers in the Lockridge survey is shown in Figure 2. The figure shows a mainly limestone section (in pink) sandwiched between two clastic sections. Embedded within the limestone section is a halite section (in green). However, the halite section in the east part of the figure was eroded with time, while the western portion survived. As a result of this erosion, the limestone section appears considerably thinner in the eastern portion of the figure, while the upper clastic section is thicker there than it is on the west side. Given that the sound velocity in limestone is considerably larger than it is in clastic sections, it is expected that the spatial variation in the thickness of the near-surface layers will cause travel time distortions associated with seismic waves reflecting from much deeper rock interfaces. It is desirable to remove this distortion by obtaining a 3-dimensional model of the near-surface rocks so that their influence on travel times can be accounted for.

To obtain a near-surface model, we applied the generalized linear inversion algorithm as implemented in the software package GLI3D. Three layers were modeled, the two clastic sections plus the limestone layer. For simplicity, the halite section was considered as part of the limestone layer instead of being treated as a separate layer. Two areal maps corresponding to the computed thicknesses of the upper clastic layer and the limestone layer, respectively, are shown in Figure 3. In this figure, the cold colors (blue and green) correspond to thin sections, while the hot colors (red and purple) correspond to thick sections. The cross-section shown in Figure 2 corresponds to an east-west line through the middle of the maps, as indicated by the thin white rectangle in Figure 3. Note the increased thickness of the upper clastic layer in the south east and north east areas of the map. These are the areas where the halite is expected to have eroded over the geologic times. On the other hand, the solution corresponding to the limestone layer shows noticeable thinning in the same south east and north east areas. Recall that these models were obtained simply by inverting measured travel times corresponding to waves that have critically refracted and traveled along the boundaries of the layers in question.

Now, consider a seismic shot panel, which consists of the collection of all receivers associated with a given source. If one were to display the traces recorded at each of such receivers side-by-side, one obtains a picture of travel times displayed as a function of the source-receiver distance, h. Equations (2-3) indicate that, at least for the early arrivals associated with near-surface layers, a distortion-free environment would result in time functions that are piecewise linear in h. To examine the quality of the model obtained in our survey, we show in Figure 4 two shot panels displayed before the application of static corrections (lower pictures) and after the application of static corrections (upper pictures). The figure shows clearly how refraction static corrections were able to compensate for the distortions associated with the spatial variations of the near-surface layers.

5. CONCLUSION

The main objective of this paper is to hightlight one of several nonlinear inverse problems encountered in the area of seismic data processing. The problem chosen here is that of modeling the near-surface rock layers. A basic formulation of the problem is given, together with a brief description of a widely used approach for solving it — the generalized linear inversion algorithm. The results of our experience with this algorithm for modeling near-surface layers from west Texas are given.

6. REFERENCES

[1] M. L. Dobrin (1976), *Introduction to Geophysical Prospecting*, Third Edition, McGraw-Hill, New York.

[2] D. Hampson and B. Russell (1984), "First-Break Interpretation Using Generalized Linear Inversion," *Journal of the Canadian Society of Exploration Geophysicists*, vol. 20, no. 1, pp. 40–54.

[3] Hampson-Russell Software Services, Ltd. (1990), "GLI3D: Three Dimensional Refraction Analysis," Program Documentation, Calgary.

[4] D. Marsden (1993), "Static Corrections - A Review," *The Leading Edge*, Part I pp. 43–49, Part II pp. 115–120, Part III pp. 210–216.

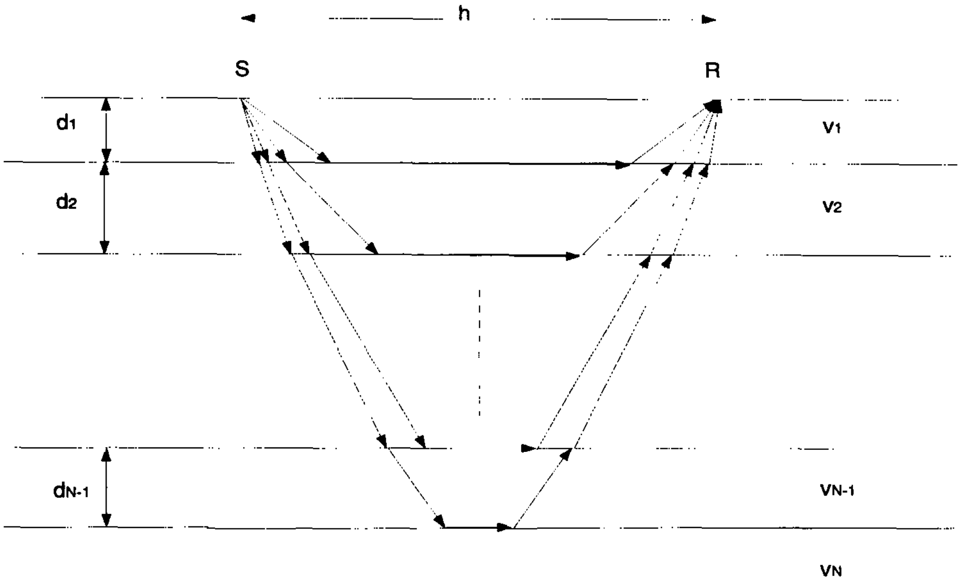

Figure 1: Rays associated with critically refracted waves.

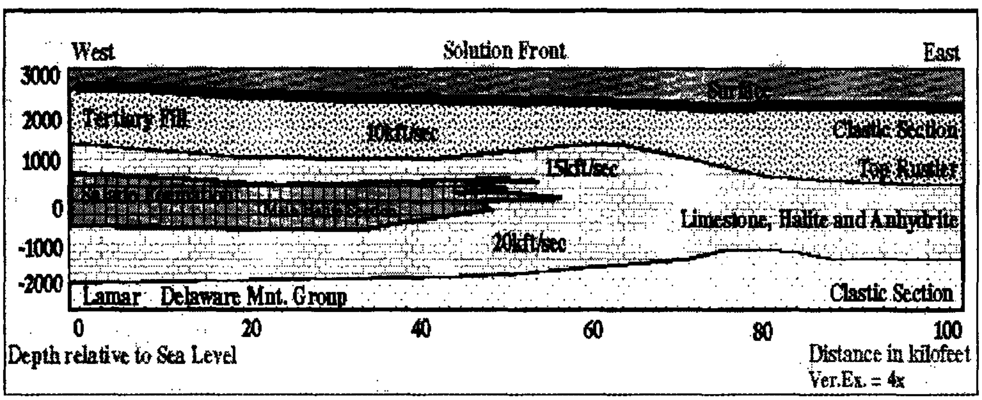

Figure 2: Geologic cross-section from the Lockridge survey.

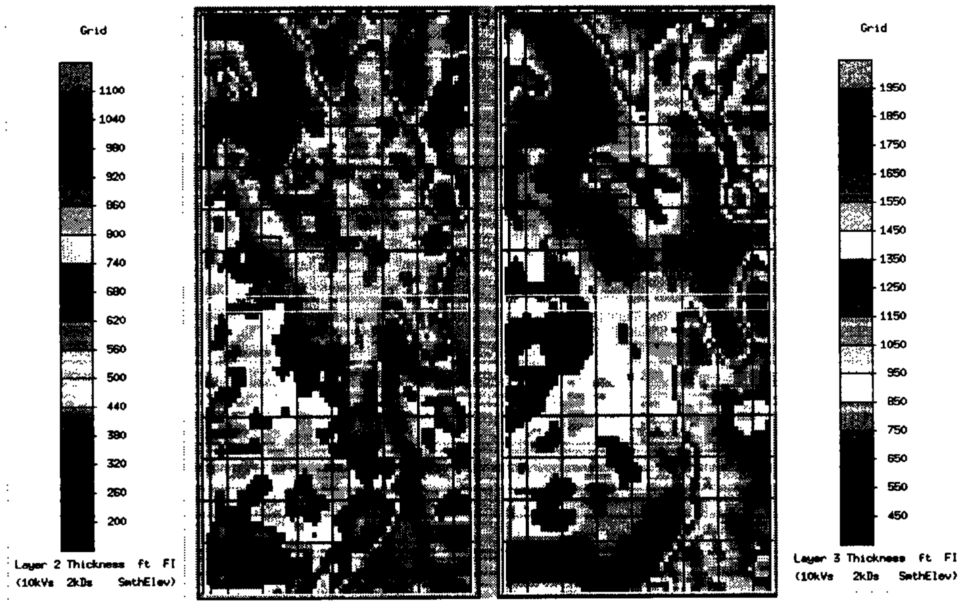

Figure 3: Thickness maps for the upper clastic section (left) and the limestone section (right).

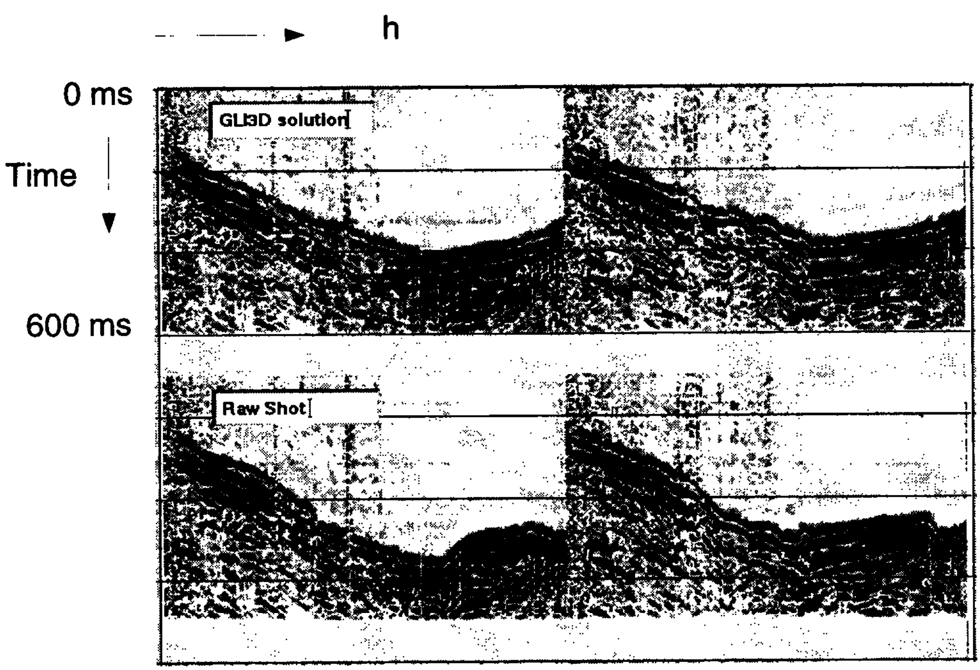

Figure 4: Two source panels: Before (lower two) and after (upper two) application of refraction static corrections.