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Application of 3D statics technology and seismic interferometry to Engineering Geophysics

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Introduction

This paper presents the application of 3D statics used in oil exploration industry to Engineering Geophysics, and an attempt to prove the unicity of inverted solutions with an analysis of amplitudes of refracted first arrivals.

The principle of one of the most renowned method, the Plus-Minus method (Hagedoorn, 1959), has been improved by Dereck Palmer (1981) with the General Reciprocal method (GRM). Later on, the same author (reference needed) outlined a problem of non-unicity of inversions which can be supported with the following question; is the interface of a refractor dipping or is the velocity varying laterally?

Palmer (2000) proposed a solution through the analysis of refracted amplitudes, with a technique alled Refraction Convolution section, or RCS. Different cases show that the smaller is the amplitude, the higher is the impedance contrast between layers on top and beneath a same refractor. If the amplitude remains constant along a delineated refractor, change in time-depth is related to a change in depth of the refractor. On the other hand, if amplitude varies laterally along a same delineated refractor, the change in time-depth is related to a lateral change in velocity.

De Franco (2005 & 2011) has since refined this method by processing seismic refraction data like seismic reflection data. The outcome of this sophistication is a time depth seismic refraction section, and the ability to delineate many refractors. Information on amplitudes is cleaner, and determining in solving non-unicity related problems.

For example, Palmer recommends the use of the information held in amplitudes for defining an initial model before starting a tomography based inversion, the role of the later technology becoming increasingly more important with the need to get 3D pictures of the first 30 meters subsurface.

Unfortunately, the downside of 3D seismic methods for near surface investigations is its cost related to the increasing number of shots and geophones required by a survey. This paper discusses some recent work by Limacher et al. (2011) who proposes to bypass this economical problem by not using tomography, but a conventional 3D tool for computing statics in oil industry. Because it requires less ray-paths between shots and geophones, this tool allows us to reduce the costs by performing a 3D survey with a conventional subsurface equipment made of 24 channels. The relevance of the inverted model will be assessed by analyzing the phases of the different traces composing a seismic refraction section made with the procedures defined by De Franco (2005 & 2010), who used techniques from seismic interferometry.

Method and/or Theory

3D refraction statics

The scope of this paragraph is to summarize a method based on intercept times, described by Cox (1999) and implemented in this paper for inverting refracted seismic arrivals from a shallow 3D multilayered configuration. The principle of its application is in seven steps (see Figure 1), with computations of:

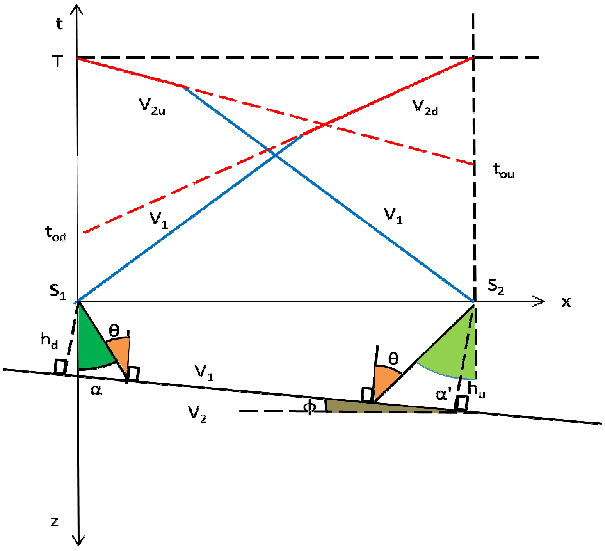


Figure 1- Example of depth computation of a refractor with the algorithm defined by Cox (1999)

1. the angle of emergence α: $sin(\alpha) = v_1/v_{2u}$ (Equation 1)
2. the angle of emergence α': $sin(\alpha') = v_1/v_{2d}$. (Equation 2)
3. the angle dip: $\phi = (\alpha' - \alpha)/2$ (Equation 3)
4. the critical angle for the interface: $\theta = (\alpha + \alpha')/2$ (Equation 4)
5. V_2: $v_2 = \frac{v_1}{\sin((\alpha+\alpha')/2)} = \frac{v_1}{sin(\theta)}$ (Equation 5)
6. h_d and h_u: $h_d = \frac{t_{od}}{2}\frac{V_1}{cos(\theta)}$ and $h_u = \frac{t_{ou}}{2}\frac{V_1}{cos(\theta)}$ (Equations 6,7)
7. depths z_d and z_u (vertically beneath S1 and S2): $z_d = \frac{h_d}{cos(\alpha)}$ and $z_u = \frac{h_u}{cos(\alpha)}$ (Equation 8,9)

Where V_i is the velocity and h_i the thickness in the i^{th} layer, t0 the intercept time, and subscripts u and d stand for updip and downdip.
Generalization to a multilayer case relies on the following expression:

$$t_{0(n-1)} = \sum_{i=1}^{n-1} \frac{2h_i}{V_i} cos(\theta_{in})$$ (Equation 10)

used for deducing, layer by layer, the respective depths and thicknesses of refractors, where the term n stand for the n^{th} layer, and θ_{in} is the angle subtended in layer i for a refraction in layer .
Generalization in 3D is done with the Gauss-Seidel method. As this iterative method requires a matrix to be either diagonally dominant, or symmetric and positive definite, a compromise has to be found between resolution and stability of the inversion. If this mathematical requirement is properly considered in both 3D geometry design and data processing, users can fully take advantage of the fast convergence inherent to this numerical method, which make this generalization to 3D so computationally effective.

2D Seismic Refraction Section and amplitude analysis

Theory of 2D seismic refraction sections is based on both Generalized Reciprocal Method and seismic interferometry. Generalized Reciprocal Method requires the computation of a time depth function:

$$T_G(K) = T_J(X_{K+m}) + T_I(X_K) - T_J(X_I)$$ (Equation 11)

and a velocity function

$$T_V(K) = (T_J(X_{K+m+g}) - T_I(X_K) + T_J(X_I))/2$$ (Equation 12)

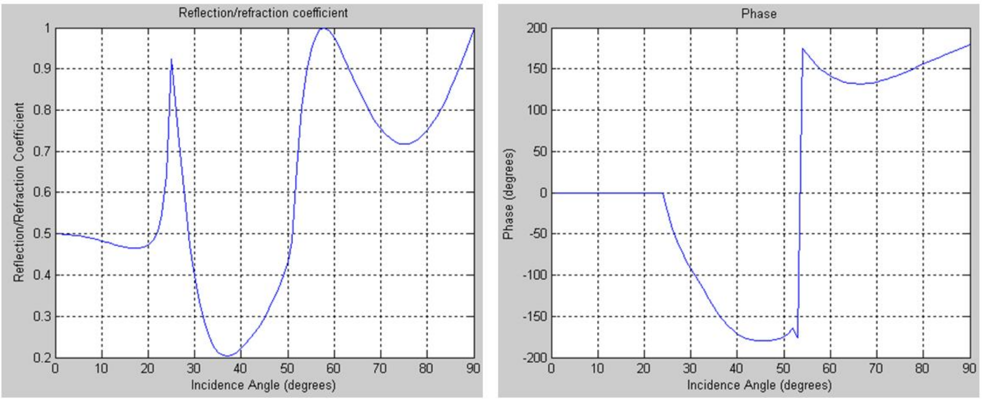
$$\frac{dT_V}{DX} = \frac{1}{V_n}$$

(Equation 13)

Where m, g and $T_i(X_j)$ are the migration parameter, geophone step, and the traveltimes of different refracted rays.

Equations 11, 12 and 13 are implemented with seismic interferometry by considering that convolution add travel-times, while correlation subtracts them. For preventing any mathematical artifact linked to the inter-correlation/convolution between surface and air waves, the coda wave is muted, and only the first pick and trough remain.

Finally, amplitudes of cross-convolved/correlated traces are analyzed by considering the Zoeppritz equations and their analytical solutions defined by Aki and Richards (2002), which state that reflected amplitude of seismic waves varies with the initial angle of incidence. This same analytical solutions states that for refracted waves, beyond the critical angle, variation of amplitude with angle of incidence is coupled to a variation of phase of the trace, as shown in Figure 2. Recollection of this phase will be determined in proving the relevance of an inversion.



(a) (b)

Figure 2 - Examples of (b) phase and (a) reflection/refraction amplitude variations of seismic waves with incidence angle. Beyond the critical angle, at approximately 25 degrees, incidence angle induces a phase. It means that dip of a refractor can be recovered from a constant incidence angle(from Limacher et al,2011)

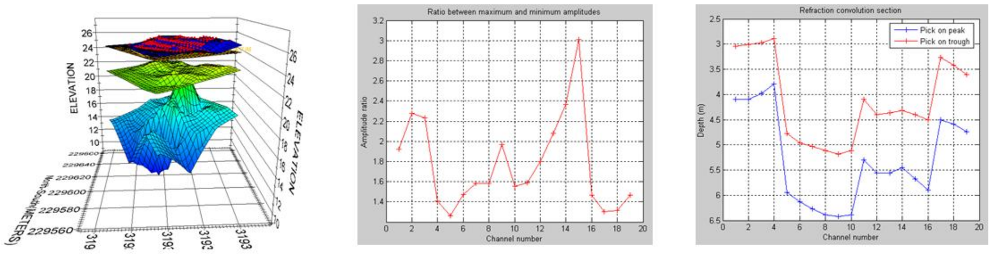
Conclusions

As shown in figure 3-(a), a technique from oil exploration industry for computing 3D statics has conclusively been used for engineering geophysics purposes. Despite the relevance of the inversion results obtained from different sites in University College Dublin and in Ireland, concerns on non-unique solutions of inversions raised by Palmer (2010) have been taken into account, and led us to consider an analysis of refraction amplitudes with a technique based on Refraction Convolution Section, and refined by De Franco (2005 & 2011) with principles from Seismic Interferometry.

Refracted waves have been analyzed by considering variation of amplitudes with offset, like in an Amplitude Versus Offset (AVO) analysis. In the refracted wave's case, this variation of amplitude is coupled to a variation of phase; it means that the dip of a refractor can be recovered if we use a constant angle of incidence. Different cases of phase graphs correlating or contradicting inversion results will be presented during the conference, in order to assess the reliability of the interpretation technique of data from 3D refraction surveys (by comparing figure 3-(a) to figures 3-(b) and (c)).

On the short term, this technique, which is not based on tomography, opens the prospect of reducing the costs related to 3D refraction surveys, in order to make them more affordable to civil engineering and environmental geophysics.

On the longer term, this work shows how a combination of Refraction Convolution Section, Seismic interferometry and AVO analysis can be helpful in assessing the relevance of an inversion result, and may open the prospect of recovering more information on the lithology (like the density) from seismic refraction data.



(a) (b) (c)

Figure 3 - Examples of a correlation between (a) a 3D refraction survey, (b) a 2D phase plot (Limacher and al, 2011) and (c) a 2D refraction profile (Limacher and al, 2011).

Acknowledgements

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