Combining elevation and NMO corrections to shallow seismic reflection data on rugged topography

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Summary

The application of the seismic reflection method is often limited in complex terrain areas. The problem is the incorrect correction of time-shifts caused by topography. To apply normal moveout (NMO) correction to reflection data correctly, static corrections are necessary to be applied in advance for the compensation of the time distortions of topography and the time-delays from near-surface weathered layers. For environment and engineering investigation, weathered layers are our targets so that the static correction mainly serves the adjustment of time-shifts due to an undulating surface. In practice, seismic reflected raypaths are assumed to be almost vertical through the near-surface layers because they have much lower velocities than layers below. This assumption is typically acceptable in most cases since it results in little residual error for small elevation changes and small offsets in reflection events. Although static algorithms based on choosing a floating datum related to common midpoint gathers or residual surface-consistent functions are available and effective, errors caused by the assumption of vertical raypaths often generate pseudo-indications of structures. This paper presents the comparison of applying corrections based on the vertical raypaths and bias (non-vertical) raypaths. It also provides an approach of combining elevation and NMO corrections. The advantages of the approach are demonstrated by a synthetic example of multi-coverage seismic reflection surveys on rough topography.

Introduction

Most static technologies are based on the assumption of vertical raypaths. This assumption is typically acceptable in most cases since it results in little residual error for small elevation changes and small offsets in reflection events. Applying corrections under this assumption is an attempt to reduce the real observed near surface to an assumed plane so that time-distance relationships of disturbed reflections can be described by hyperbolas. Marsden (1993b) provides a nearly complete discussion about technologies that reduce errors of elevation corrections and enhance the quality of seismic sections, e.g., linear travel-time inversion techniques for finding optimized shift times by cross-correlations of traces (Taner et al., 1974; Saghy and Zelei, 1975), surface-consistent residual static estimation by stack power maximization methods (Ronen and Claerbout, 1985), and time-variant statics corrections (Musgrove, 1994). Based on the fact that refracted and reflected waves pass through the weathering layer with similar paths, Hatherly et al. (1994) presented a refraction-statics method. Before static corrections can be applied, it is necessary to select a suitable reference datum. To keep statics corrections small, a floating datum is usually used until NMO correction has been applied (Marsden, 1993a).

The assumption of vertical raypaths where topography is rugged, however, could result in inaccurate elevation corrections. Furthermore, errors caused by inaccurate elevation corrections could pass only the NMO corrections. For a horizontal reflector underlying a constant-velocity overburden, the reflection t-x curve observed on a horizontal surface will be a branch of the hyperbola

$$t_x = \sqrt{t_0^2 + \frac{x^2}{v^2}} \quad \text{with} \quad t_0 = 2d/v\,, \tag{1}$$

where t_x is the reflection travel-time with x the source-receiver offset, t_0 is the normally incident reflection time at the midpoint between source and receiver, d is the reflector depth, and v is the velocity. For a multi-coverage seismic survey, the *t-x* equation of each trace in a common-midpoint (CMP) gather can be written as equation (1). When the observing surface is not flat, the reflection travel-time changes with the elevations of source and receiver stations. In general, corrections need to be done prior to further data processing. Under the assumption of vertical travel paths in the near-surface, the contribution to travel-time for a specific source-receiver pair can be estimated by source and receiver station elevations Δh_s and Δh_r, respectively, relative to some datum level, i.e., $\Delta t_e=(\Delta h_s + \Delta h_r)/v$. Δt_e is taken as the compensation for the time-shifts due to topography. Supposing the earth or rock between the surface and target-layers is almost homogeneous, the travel-time relative to the datum is $t_x' = t_x+\Delta t_e$. This routine is inaccurate, especially in multi-coverage seismic surveys over mountainous areas. The elevation correction Δt_e, based on vertical travel-time, may cause significant errors to the sequent stacking and velocity analysis.

The static anomalies distort first, and most directly, the estimation of stacking velocities for the NMO correction. Difference in raypaths can be caused by errors of the static correction, especially in the area with great change of elevations. Errors, contained in traces of each CMP gather, influence the estimation of stacking velocities. Inappropriate estimation of velocities sequentially results in a loss of seismic resolution, increased mis-ties of seismic events at intersections, and production of false structural anomalies. An accurate expression can improve the quality of static corrections and velocity analysis, which provides an approach, based on the bias raypaths, to perform the elevation and the NMO correction simultaneously. We will discuss the accurate expression in the following section.

Reflection time-distance equation on an uneven surface

The exact t-x equation for a source-receiver pair of a CMP gather from an uneven observation surface, referring to Figure 1, can be written as

$$\tilde{t}_x = \frac{\overline{S^* R}}{v} = \sqrt{\frac{x^2 + [(h_s - h_{reflector}) + (h_r - h_{reflector})]^2}{v^2}}, \quad (2)$$

where $h_{reflector}$ is the reflector elevation, and h_s and h_r are the source and receiver elevations, respectively. In the right side of equation (2) the terms $(h_s - h_{reflector})$ and $(h_r - h_{reflector})$ can be replaced by $[(h_s - h_m) + (h_r - h_m) + 2(h_m - h_{reflector})]$, in which h_m is the elevation of the midpoint of a source-receiver pair on the surface. Defining $d_m = (h_m - h_{reflector})$ as the elevation difference from the midpoint of a source-receiver pair to the reflector shown in Figure 1, and $\Delta h_{sm} = (h_s - h_m)$ and $\Delta h_{rm} = (h_r - h_m)$ as elevation differences from source and receiver to midpoint, respectively, the travel-time may be described by

$$\tilde{t} = \sqrt{\frac{x^2}{v^2} + \left(\frac{\Delta h_{sm} + \Delta h_{rm} + 2d_m}{v}\right)^2} = \sqrt{\frac{x^2}{v^2} + \left(t_{m0} + \frac{\Delta h_{sm} + \Delta h_{rm}}{v}\right)^2}, \quad (3)$$

where $t_{m0} = 2d_m/v$ is the normal-incidence reflection time at the midpoint of the CMP gather. Supposing $(\Delta h_{sm}+\Delta h_{rm}+2d_m) >> x$ and $(\Delta h_{sm}+\Delta h_{rm}) << 2d_m$, expanding the square-root expression on the right side of equation (3) by Taylor-series and ignoring the second-order and higher terms, we have an approximate form

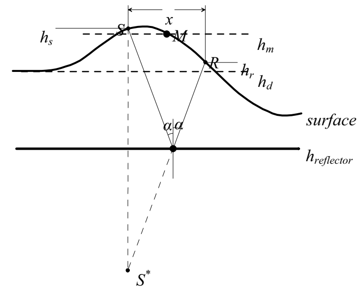

Figure 1. The reflection raypath from source S to receiver *R*. The geometrical relationship of the raypath with the elevations of source, receiver and reflector is shown through the imaged source S^*.

$$\tilde{t}_x \approx \frac{\Delta h_{sm} + \Delta h_{rm} + 2d_m}{v} + \frac{x^2}{4vd_m} - \frac{x^2}{8vd_m^2}(\Delta h_{sm} + \Delta h_{rm}) = t_{m0} + \frac{x^2}{2t_{m0}v^2} + \frac{\Delta h_{sm} + \Delta h_{rm}}{v} - \frac{x^2}{2t_{m0}^2 v^3}(\Delta h_{sm} + \Delta h_{rm}) \cdot \quad (4)$$

The second term on the right side of equation (4) is the NMO. While $x \ll 2d_m$, the sum of the first three terms is equivalent to the travel-time t'_x. The elevation correction $(\Delta h_{sm}+\Delta h_{rm})/v$ can be considered referring the datum on the midpoint level. Comparing $\tilde{t}_x$ with t'_x, we have the difference

$$\delta_e = -\frac{x^2}{2t_{m0}^2 v^3}(\Delta h_{sm} + \Delta h_{rm}) \cdot \quad (5)$$

Apparently, using only Δt_e to correct for terrain variations may cause overcorrection when $(\Delta h_{sm}+\Delta h_{rm}) > 0$ or undercorrection when $(\Delta h_{sm}+\Delta h_{rm}) < 0$. Thus an inexact static correction generates static anomalies.

According to the discussion above, we should use the accurate expression of time-shifts (NMO plus the elevation correction) from an irregular observation surface, that is

$$\Delta\tilde{t} = \sqrt{\frac{x^2}{v^2} + \left(t_{m0} + \frac{\Delta h_{sm} + \Delta h_{rm}}{v}\right)^2} - t_{m0} \cdot \quad (6)$$

For comparison, the conventional time-shift (NMO and elevation corrections) can be expressed as

$$\Delta t = \frac{x^2}{2t_{m0}v^2} + \frac{\Delta h_{sm} + \Delta h_{rm}}{v} \cdot \quad (7)$$

A synthetic example

The major objective of calculating a velocity spectrum is to ascertain the amount of the normal moveout that should be removed to maximize the stacking energy of reflection events. As a coherence measure for a number of traces, the semblance measure (Neidell and Taner, 1971) is a useful quantity that denotes the ratio of the total stacking energy within a time gate to the sum of the energy of the component traces. We compute velocity spectra as in Neidell and Taner's approach (1971) with $\Delta\tilde{t}$ and Δt as alternative expressions for moveout. In order to illustrate the results for the two correction approaches, we designed a substructure model with four horizontal reflectors with an uneven observing surface (Figure 2). The data acquisition was assumed to be along the model section shown in Figure 2 by using the CMP acquisition method (Mayne, 1962). A standard Ricker wavelet (Sheriff, 1991, p. 255) with a dominant frequency of 100 Hz is used in the modeling, the record length was set at 250 ms, and the sampling interval at 0.25 ms. The CMP spread was designed with a minimum offset of 10 m, twelve traces per gather, and a trace spacing of 10 m.

Stacking velocities (Figure 3) determined by using the velocity scan at CMP58, CMP74, CMP90 referring the datum level h = 0 with equations (7). We can find a relatively big difference in calculated velocities and model velocities at CMP58 and CMP90, especially for the shallow layers. Stacking velocities (Figure 4) are determined by using the velocity scan at CMP58, CMP74, and CMP90 with equation (6). Velocity scan based on equation (6) provides the more accurate stacking velocities (Figure 4) than those in Figure (3). Moreover, it does not need any reference datum.

CMP stacking results based on conventional time-shift Using equation (7) to compensate the time shifts for stacking is a conventional approach. It requires that simple vertical path elevation corrections be done before NMO corrections are applied. When a seismic reflection survey is carried out in an area with an uneven surface, data processors generally prefer to select the level of average elevations in the field area as the datum. For this model we took the level h = 0 as the datum and applied static corrections to the synthetic records. Subsequent results of velocity analysis reveal different stacking velocities at different locations along the line. Because the symmetry of residual relief, the calculated velocities based on the spectrum (Figure 3) are close to the velocities of the model at CMP74, much as those where the surface is horizontal. Figure 5 shows the stacked section based on the floating datum with stacking velocities determined in Figure 3.

CMP stacking results based on the accurate moveout For the bias (non-vertical) raypaths in the near-surface, equation (6) provides an accurate formula for simultaneously calculation of the NMO of each trace and static corrections rather than first calculating the static corrections and then applying NMO correction. The time difference in equation (6) incorporates the influence of both topography and the normal moveout. The time correction of each trace in a CMP gather relative to the travel time at the midpoint can be estimated more accurately. All stacked CMP traces will still need to shifted to the datum of the whole seismic survey for the purpose of mapping since the moveout corrections for each CMP gather are computed relative to its midpoint level. A static correction is applied to a stacked section to a horizontal datum, which is accomplished by applying the simple elevation correction based on vertical raypaths to each stacked CMP gather at its midpoint. Figure 6 shows an almost perfectly stacked section with stacking velocities determined in Figure 4 after shifting all stacked CMP traces to the datum of the whole seismic survey. Only small velocity differences remain between calculated velocities and the model velocities.

Conclusions and future studies

On uneven topographic surfaces, the time-distance curve of a common-midpoint reflection after conventional elevation correction is not a hyperbola. The reflection events exhibit a smaller moveout on raised surfaces and a larger moveout on sunken surfaces, so that reflection events may cross each other. This leads to misunderstanding to the existence of structures. In this case, conventional static correction methods fail to find accurate time-shifts owing to overcorrection or undercorrection. Accurate moveout, which is based on the bias raypaths, can find accurate stacking velocities. Theoretically, the inversed velocities from the velocity spectrum analysis are not related to the topography. In other words, rugged topography has no effect on determination of stacking velocities. The synthetic example demonstrated accuracy of moveout of seismic reflection data on a rugged topography. The approach is waiting to be applied to real data to test its feasibility in the real world. Authors welcome real data set that will be used to test the approach.

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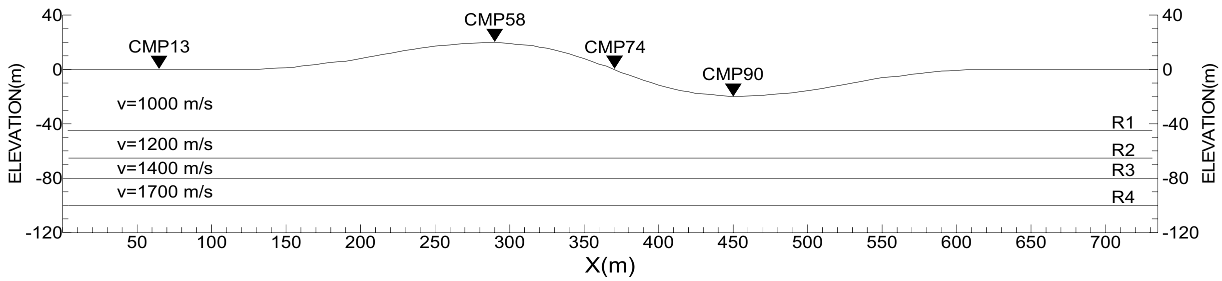

Figure 2. Four flat sub-surfaces lie under an uneven surface and are of increasing velocity from the top to bottom. Layers have constant traverse velocities and various thicknesses. The four midpoints of CMP are respectively marked at hill (CMP58), brae (CMP74), valley (CMP90) and flat (CMP13) areas on the surface.

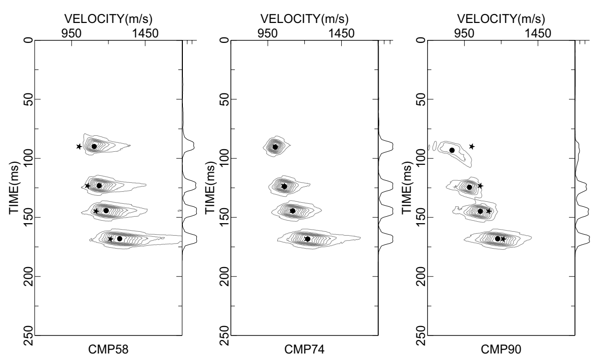

Figure 3. Velocity spectrum. Stacking velocities determined by using the velocity scan at CMP58, CMP74, CMP90 referring the datum level h = 0 with equation (7). In each graph the symbols "★" and "●" indicate real velocities and calculated velocities based on the spectrum, respectively.

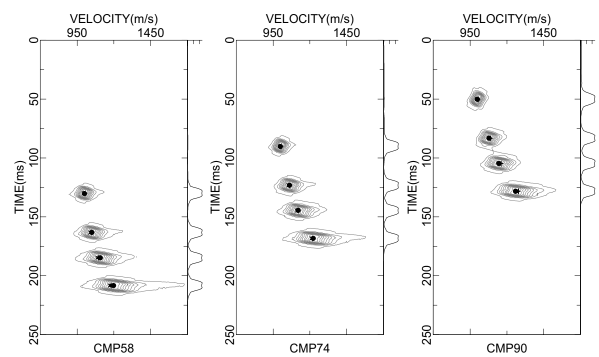

Figure 4. Velocity spectrum. Stacking velocities are determined by using the velocity scan at CMP58, CMP74, and CMP90 with equation (6). In each graph the symbols "★" and "●" indicate real velocities and calculated velocities based on the spectrum, respectively.

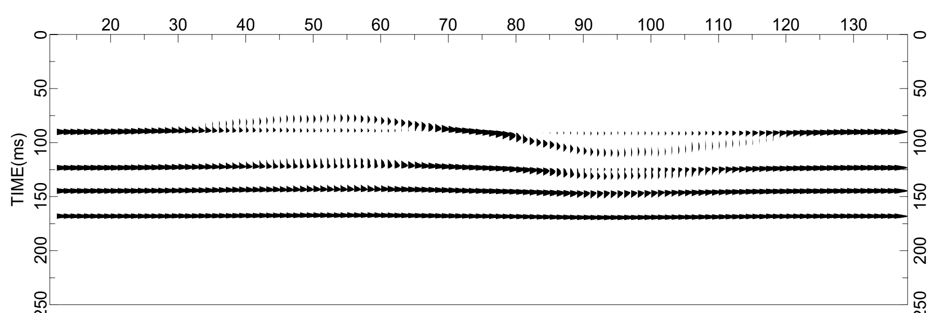

Figure 5. The stacked section after NMO and elevation corrections with equation (7) have been applied referring to the float datum. The x-axis is CMP number.

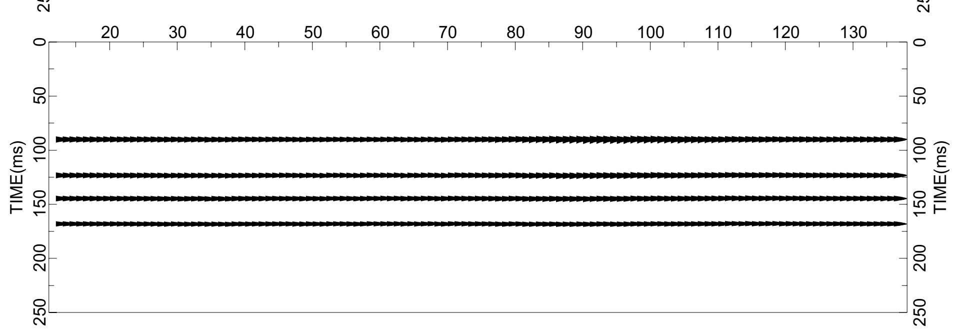

Figure 6. The stacked section with corrections completed. These correction included NMO and elevation (equation 6), and time-shift to reduce stacked CMP gather to the flat datum. Events (reflectors) are clearly indicated. The x-axis is CMP number.