Deriving Interval Velocities from Downhole Seismic Data

When analyzing downhole seismic testing data in soil profiles with minimal variance in impedance between the various soil layers, the *Straight Ray Assumption* (*SRA*) methodology can be utilized to calculate interval velocities. Referring to Fig. 1a, the interval velocities from the SRA method are obtained by calculating the relative arrival time differences (e.g., $\Delta T = T_2 - T_1$) between two successive depths z_2 and z_1 and by assuming straight ray travel paths from source to receiver when calculating travel path differences.

Example:

$$d_1 = \sqrt{l_1^2 + z_1^2}, \qquad d_2 = \sqrt{l_2^2 + z_2^2} \tag{1}$$

where z_1 is the vertical depth of the seismic sensor package at interval index 1, l_1 is the source-sensor radial offset at interval index 1, d_1 is the travel distance of the source wave to interval index *1* assuming a straight ray trajectory, z_2 is the vertical depth of the seismic sensor package at interval index 2, l_2 is the source-sensor radial offset at interval index 2, d_2 is the travel distance of the source wave to interval index 2 assuming a straight ray trajectory. The *SRA* interval velocity between depth increments 1 and 2 is then calculated as follows

$$V_2 = \frac{d_2 - d_1}{\Delta T} \tag{2}$$

A standard straight ray geometry assumes that the down going rays have spent an equal amount of time or have the same travel path within each interval layer as is shown in Fig. 1(a). The slant ray and refraction calculation take into account the time spent and corresponding travel path within each layer as illustrated in Fig. 1(b) (e.g., D1, D2A and D3A within layer 1, D2B and D3B within layer 2 and D3C within layer C).

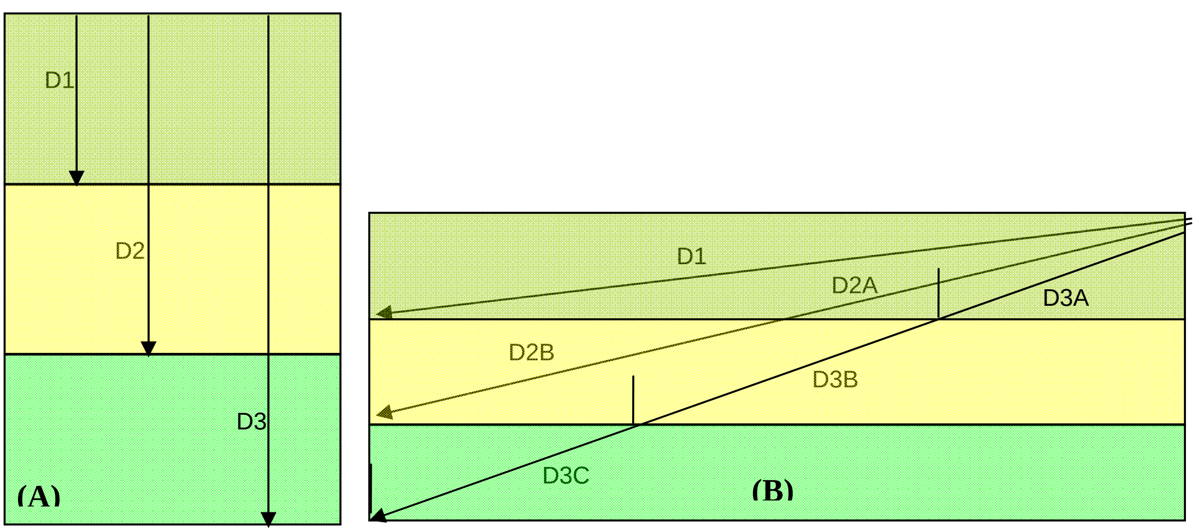

Figure 1. (a) Straight ray assumption. (b) Slant ray assumption.

However, source wave trajectories also adhere to *Fermat's principle*, which means that the raypath travels along the trajectory which requires minimum time between points. To properly account for this in soil profiles with significant variance in impedance between the soil various layers, the calculation of the interval velocities should no longer be based on the SRA methodology, but instead use the *Iterative Forward Modeling* (IFM) technique. This technique has many advantages over the *SRA* technique, such as:

1. The refraction of the raypath at layer boundaries is considered using Snell's Law.
2. Fermat's Principle of least time is adhered to.
3. Optimal interval velocity estimates are obtained by minimizing a nonlinear cost function.
4. Extensive downhole time series measurement information (e.g., arrival times, cross-correlation time shifts, P-S wave time separation, and angles of incidence) can be taken into account within the nonlinear cost function.
5. Measurement weights can be specified.
6. Slant ray raypaths are taken into account
7. The determination of meaningful error residuals for the evaluation of the accuracy of the estimated interval velocity.

The ability of the IFM technique to improve upon the SRA interval velocity estimates depends on several site parameters such as radial seismic sensor - source offset, depth of interval velocity estimate, and variability of the *in-situ* velocity profile. Fig. 2 illustrates a simulated seismic test where the seismic source is radially offset from the seismic probe by 2.1 m, the seismic data capture starts at 1.5 m and goes to a depth of 7.5 m at one meter intervals. As it is simulated, the true interval velocities in each layer are known.

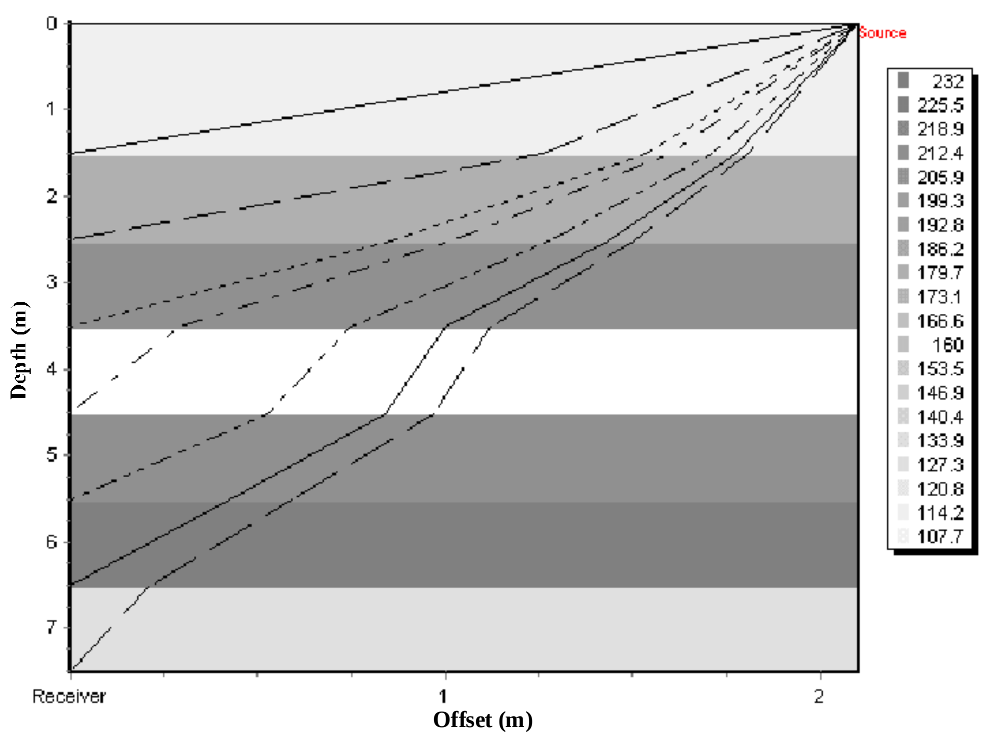

Figure 2. Specification of a seven layer variable velocity interval stratigraphic profile for comparing the performance of the IFM and SRA analysis techniques.

Table 1 outlines these true interval velocities as well as the estimates using either the *IFM* technique or the *SRA* technique. As shown in this table, the IFM exactly recovered the true interval velocities and provided the source receiver ray paths illustrated in Fig. 2. The SRA interval velocity estimates did a poor job in estimating the true interval velocity estimates due to the site parameters specified being poorly conducive to a straight ray assumption.

Table 1. Interval velocities – actual and estimated

Interval Depth (m)	Arrival Time (ms)	True Interval Velocities (m/s)	IFM Interval Velocity Estimate (m/s)	Straight Ray Interval Velocity Estimate (m/s)
0-1.5	22.9795	112	112	112
1.5-2.5	24.2555	181	181	536
2.5-3.5	27.3112	209	209	267
3.5-4.5	36.6900	101	101	94
4.5-5.5	40.7033	214	214	230
5.5-6.5	44.5370	232	232	246
6.5-7.5	52.1200	128	128	126

The application of the IFM technique becomes even more essential in case of a soil profile with a top layer that has a relatively low interval velocity. In that case the arrival time in a deeper layer may occur prior to that in a shallower layer, as illustrated in Fig. 3 and Table 2, which lists the arrival times and the interval velocities obtained with the IFM technique.

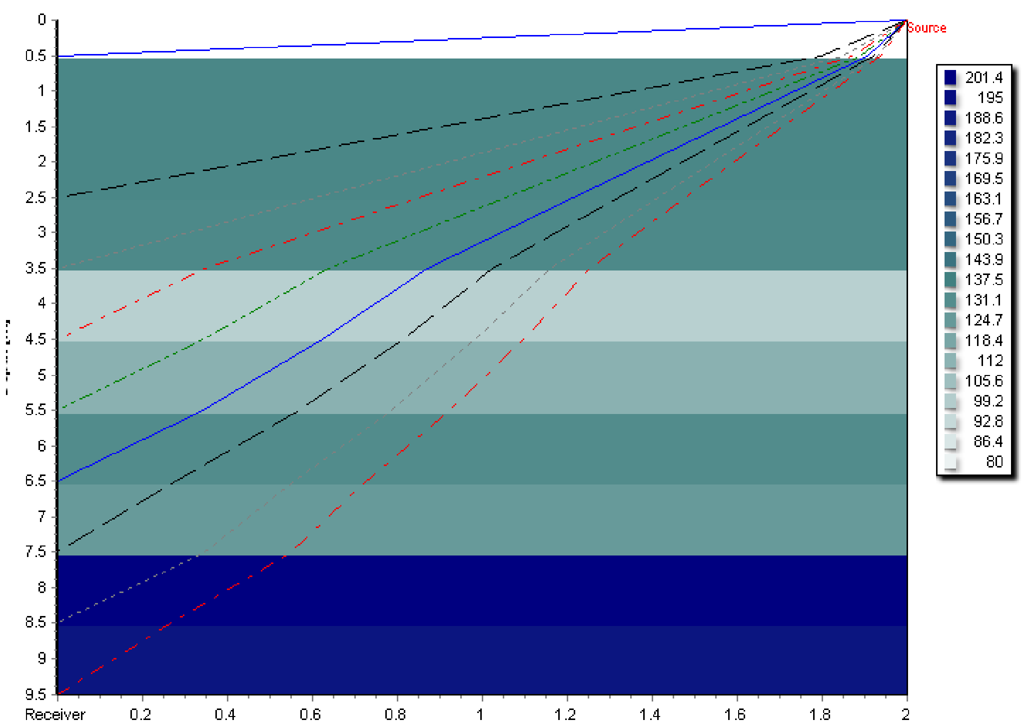

Figure 3. Specification of an eight layer variable velocity interval stratigraphic profile to illustrate that the arrival time in a deeper layer can occur before that in the layer immediately above.

Table 2. Interval velocities – actual and estimated

Interval Depth (m)	Arrival Time (ms)	IFM Interval Velocity Estimate (m/s)
0-0.5	28.000	73.6
0.5-2.5	27.4555	134.1
2.5-3.5	33.5112	133.1
3.5-4.5	43.0900	97.3
4.5-5.5	51.4033	112.8
5.5-6.5	58.5370	131.6
6.5-7.5	66.2310	124.5
7.5-8.5	70.8411	201.4
8.5-9.5	75.8290	190.8

It shall be obvious that in cases like this the use of this technique is absolutely essential (e.g., for depth interval 0.5m to 2.5m the SRA would have given a negative interval velocity), and this may also explain why according to some the use of downhole seismic testing is not appropriate for shallow depths. It may well be that the applied data analysis method was not appropriate and that the Iterative Forward Modeling technique would have generated accurate results. Finally it demonstrates the importance to know the analysis method used when reviewing interval velocity data.

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BCE's Seismic Data Analysis software packages SC1-RAV, SC3-RAVand VSP-IMV provide the user the option of applying the Iterative Forward Modeling technique. For more information about these packages (incl . a copy of the user manual please visit our website (www.bcengineers.com)) or contact our offices:

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