Seismic Reflection Method

*Top:* Monument unveiled in 1971 at Belle Isle (Oklahoma City) on 50th anniversary of first seismic reflection survey by J. C. Karcher. *Middle:* Two early
reflection records from Belle Isle, 1921. Bottom: Karcher's interpretation of same.

- uses reflected energy from interfaces between subsurface layers to determine their configuration
- reflections recorded as two-way (down and back up) travel times, not depths
- fraction of incident energy reflected from interface called reflection coefficient
- dependent on acoustic impedance contrast across interface

Reflection Coefficient = \( \frac{\text{Amplitude reflected}}{\text{Amplitude incident}} = \frac{V_1 \rho_1 - V_2 \rho_2}{V_1 \rho_1 + V_2 \rho_2} \)

where \( V_1 \rho_1 \) acoustic impedance of layer 1
and \( V_2 \rho_2 \) acoustic impedance of layer 2

Polarity of reflected wave depends on sign of reflection coefficient (unchanged polarity means compression remains compression, dilatation remains dilatation)

if \( V_2 \rho_2 > V_1 \rho_1 \) polarity of wave unchanged

if \( V_2 \rho_2 < V_1 \rho_1 \) polarity of wave reversed

<table>
<thead>
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<th>Hypothetical Rock Properties</th>
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<tr>
<td>Rock</td>
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<td>Granite</td>
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<tr>
<td>Basalt</td>
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<tr>
<td>Limestone</td>
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<tr>
<td>Sandstone</td>
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<td>Shale</td>
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For these hypothetical values, limestone-granite contact will be poor reflector

Simple Zero-offset Reflection Survey

- zero offset (distance between source and receiver)
- single layer on half-space

- reflections produce a time-section approximating interface (that even geologists can understand)
- travel time:
2 problems:
- what is $V$? [We measure $t$. If we knew $V$, we could find $d$ - convert time section to depth section.]
- energy source is expensive in time and money
solution to both problems: use geophones at different offsets

Seismic Reflection Survey with Offset, Single-fold Coverage

- record traces from several geophones spaced away from source (shot)
- display traces side-by-side, so distance between traces proportional to geophone spacing
- display increasing time downward (time approx. proportional depth)

Note that subsurface reflection points have half the spacing of geophones. To get complete "single-fold" coverage of the subsurface, can shoot from either end of geophone spread:

**FIGURE 4-1**
Obtaining continuous depth control (single fold) along profile by recording shots from opposite directions with same geophone spread. This arrangement of shots and receivers yields one trace (one fold) for each reflecting point in the subsurface.

One can also use a "split-spread" arrangement, here with shot at point B, then move half the geophones forward and shoot at C:

The next two figures show recording-truck signal check for 36-channel split-spread layout:
The travel time for the primary reflection (first layer) where geophone offset = x, thickness d, velocity V

FIGURE 4-4 Oscillographic records from four adjacent shot points set up for 100 percent coverage. Note the correlations of reflection events between records. (Amoco Production Co.)
this is a hyperbola, as we saw earlier:

\[
2 \left( \frac{x^2}{2} + d^2 \right)^{1/2} \leq t \leq \frac{\sqrt{x^2 + 4d^2} \, \gamma}{V^2}
\]

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- direct ray is straight line, per rate equation
- reflections from 1st and 2nd reflectors are not flat; reflections are hyperbolas
- because of normal moveout (NMO): reflection time increases with x, nonlinearly
- normal move-out (NMO): the difference in reflection travel-times from a horizontal reflecting surface due to variations in the source-geophone distance
- can correct for this using NMO correction, so reflections are flat
- because deeper reflectors produce flatter parabolas, NMO is less:
from before, we have:

\[ t = \frac{2 \left( \frac{x^2}{2} + d^2 \right)^{1/2}}{V} \]

\[ \Rightarrow t = \frac{x^2}{V^2} + \frac{4d^2}{V^2} \]

so the NMO is just \( t - t_0 \), where \( t_0 \) is simply \( 2d/V \)

but we don't know \( d \) or \( V \)

however,

\[ t^2 = \frac{x^2}{V^2} + \frac{4d^2}{V^2} = \frac{x^2}{V^2} + t_0^2 \]

so, plot \( t^2 \) vs. \( x^2 \):

- measure slope to get \( V \)
- intercept gives \( d \)

**Multiple Layers**

- foregoing assumed a straight-line path from source to reflector to receiver
- with multiple layers with different velocities, this clearly does not hold (actual path compared with straight-line assumption):
however, if depths are large compared to total geophone spread, error can be small

**Green Method**

- assuming straight-line paths, one can still just use a $x^2-t^2$ plot to estimate velocities and depths
- however, there is a more accurate method:

**The Dix Equation**

- uses special velocity called $V_{RMS}$
- still assumes nearly vertical incidence/straight line raypaths
- given $n$ horizontal beds, and $Dt$ is the **one-way vertical travel-time** through bed $i$, Dix equation states:

$$V_{RMS}^2 = \frac{\sum_{i=1}^{n} V_i^2 \Delta t_i}{\sum_{i=1}^{n} \Delta t_i}$$

- use $x^2-t^2$ plot to determine RMS velocities to each layer
- then can get interval layer velocities and thicknesses
- replace velocity terms by $V_{RMS}$

$$t_i^2 = \frac{1}{V_{RMS}^2} x_i^2 + t_0^2$$

- it can be shown that Dix's equation can be solved for the individual interval velocities
- in fact, the following is sometimes referred to as Dix's equation:

$$V_i^2 = \frac{V_{RMS}^2}{\Delta t_i} \left( t_{n} - V_{RMS} t_{n+1} \right)$$

- thicknesses can then be easily determined:

$$d_i = V_i \left( \frac{t_{0,n} - t_{0,n+1}}{2} \right)$$

**Velocity Scans**
Signal Summing; Stacking

- As seismic energy moves away from the source, there is a decrease in signal strength as the energy spreads out.
- This causes energy to decrease by $E = E_0/(2pr^2)$.
- Since energy is proportional to the square of the amplitude, the signal amplitude drops off like $1/r$.
- In addition, since rocks are not truly elastic (anelastic), some energy is lost to heat with every cycle, leading to an exponential loss of energy.
- Higher frequencies go through more cycles to a given depth (shorter wavelength), so high frequency energy is lost with depth.
- Taking both of these effects into consideration, we have:

$$A = A_0 \frac{r_0}{r} e^{-\alpha(r-r_0)}$$

where

$A =$ amplitude at distance $r$ from source

$A_0 =$ amplitude at distance $r_0$ from source

$\alpha =$ absorption coefficient (material dependent)

- reflections from significant depth have amplitudes that may be well below the noise level
- **summing and stacking** adds (coherent) signals and (random) noise
- improves signal-to-noise ratio ($S/N$, or $S/(S+N)$)
  - summing $n$ times increases signal by $n$
  - summing $n$ times increases noise by square root of $n$
- Example:
  - reshoot a line 36 times
  - signal increases by 36
  - noise increases by 6 (square root)
  - $S/N$ improves by $36/6 = 6$
- different means of improving S/N:

geophone groups

"Geophones are rarely used singly. Normally several (as many as 20 or more) are electrically connected to each other in a group in such a way that the outputs of the individual phones are effectively summed. The information from each group must be transmitted via cables to the recording truck. In modern land recording with 48, 96, or more group recordings, the cables are long and heavy and often add noise to the recording, especially in the presence of powerlines or water." - Dobrin and Savit, Introduction to Geophysical Prospecting, 4th ed.

- "geophone" is actually a group of geophones "tied together" in a geophone group
- signals in parallel, fed into one channel of system
- signal usually has small incident angle, reaches all geophones together (coherent)
- surface noise sweeps across geophones, tends to cancel

multiple shots

- dynamite in hole
- vibroseis trucks: multiple trucks, all in sync; shake several times
- multiple hammer blows, shotgun blasts, etc.

multi-fold coverage

- Example: 4 geophones (channels); move shot and geophones one geophone spacing and reshoot:

```
  *  +  +  +  +
  +  +  +  +  *
  +  +  +  +  +
  +  +  +  +  +
  1 1 2 2 2 2 2 2 1 1
fold coverage
```

- note that subsurface reflection points twice as closely spaced as geophones
- had we moved shot (array) 2 geophone spacings, only get single-fold coverage
- try this with different numbers of geophones and shot spacings to find a simple formula to calculate fold-coverage

Rock Velocities

- P, S velocities of various rocks (See Sydney Clark's GSA Memoir for much more)
- velocity vs. density
- velocity vs. density, part 2
- velocity vs. rock age for sandstones and shales

Data Collection

Source

Four vibroseis trucks operating in line. (Western Geophysical.)
Geophones

1. Source signal
2. Field record
   (summation of reflections A, B, and C)
3. A
4. B
5. C

Cross-correlated signal
(2) is correlated with (1)

Geophones

- Suspension springs
- Coil
- Permanent magnet

Earth
Geophones (~ $100 each) have a typical natural frequency of 10 Hz. Response is relative good over a range from about 2 Hz to 100 Hz.

Recording Digitally

- Analog signal from phones (continuous voltage vs. time)
- Sampled (typically every 2 msec) by an A-to-D (A/D) converter
- Originally integer recording
  - Example: 16-bit recording;
  - $2^{16} = 65,536$, or -32768 to +32768
  - Dynamic range of about 4.5 orders of magnitude
  - Poor resolution at low amplitudes
- Floating point recording
  - Single precision, 4 bytes, 6 digits of resolution, dynamic range $10^{1/-32}$

Seismic Reflection

http://principles.ou.edu/seismic_explo/reflect/reflect.html
Processing Steps

- At one time, greatest computing power was owned by government (mostly DOD)
- Petroleum companies ranked second
- most seismic reflection processing is computer intensive, but requires intelligent "operator" input at many steps in the process

AGC: automatic gain control

- early-arriving reflections may be orders of magnitude larger in amplitude than later ones
- AGC looks at average amplitude in a sliding time window and boosts (or attenuates) amplitude to a constant value over that window
- AGC causes loss of true amplitude information
- modern floating-point recording allows full amplitude information to be retained
- retaining "relative, true amplitude" done with linear or quadratic increase of gain with time:

\[ G(t) = kt \quad \text{or} \quad G(t) = kt^3 \]
Filtering

- remove or attenuate certain frequencies to reduce noise and improve S/N
- notch filter common at 60 Hz
- filtering often done with FFT
- filters must be "ramped" to avoid ringing (Gibbs phenomenon)
Statics Removal

Spurious structure introduced at depth by failure to take local thinning of weathered zone into account. Note magnification of relief at deep reflection because of increase in velocity.

- refraction statics - requires reversed profile
- up-hole shooting

"vertical velocity distribution near the surface determined by shooting up the hole" (Geophysical Services, Inc.):
FIGURE 7-19  Example of the improvement possible with automatic or residual static corrections. (a) Only field statics (reference-to-datum statics) applied. (b) Automatic or residual statics applied. The magnitude of the residual (automatic) receiver static applied by the program is shown in the graph on the top of the figure. The automatic statics program also calculated what residual normal-moveout corrections were necessary. Those corrections were also applied. (Western Geophysical.)
Synthetic Seismograms

(a) Stacked section

(b) Finite difference migration
The visual relationship between seismic field data, synthetic seismic data, the reflectivity time series calculated from the velocity log, and the velocity log itself. The seismic field data are displayed again next to the velocity log. Some of the major velocity boundaries are clearly visible on the seismic field data (e.g., the start of the low velocity section at 1.15 s), while others are almost indistinct, and recourse is necessary to the synthetic for character identification (e.g., the velocity increase at 0.3 s). (From Wood.10)
Seismic Reflection

Percentage of seismic activity involving various techniques. (Data from SEG annual Geophysical Activity Reports, pre-1981 data are for U.S. activity, post-1980 for worldwide activity, 3-D data from Dutt, 1992, adjusted according to judgment expressed in Goodfellow, 1991.)

Seismic Attributes

- reflections are not only information available in seismic data
- already seen value of preserving "relative, true" amplitude
- preservation and display of velocity data can reveal info otherwise missed:

Conventional B&W section on which carbonate bank would be missed:
Color display in which colors are keyed to interval velocity estimates (1000 ft/s increments):

Close-up of carbonate bank sequence seen above:
3-D Seismic Reflection

- 3-D representation ("data cube")
- migration out of plane of section (side-swipe)
- geology is, after, 3-D
- much more expensive! (~$n^2$)
3-D seismic time slices at time ranging from 1060 ms to 1260 ms:

**FIGURE 10-16** Shot and receiver locations for an entire land 3-D survey. There are 12 swaths such as the one shown in Fig. 10-15. Coverage varies over the survey from 12- to 24-fold. (NAM.)
3D visualization (caves, virtual reality, etc.)
wavelet processing

Summary of Processing Steps