

Seismic methods: Refraction II

Advanced interpretation



Refraction reading: Sharma p158 - 186

Applied Geophysics – Refraction II

594 Schedule

Tue Oct 28th	Refraction II (Hwk handed out)
Thu Oct 30th	Refraction III and Seismic Review: bring questions
Fri Oct 31 st	Hwk to Stuart (if to be returned before exam)
Tue Nov 4th	Resistivity I
Thu Nov 6th	Seismic Exam
Tue Nov 11th	Resistivity II
...	

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Real Earth "flat" layers

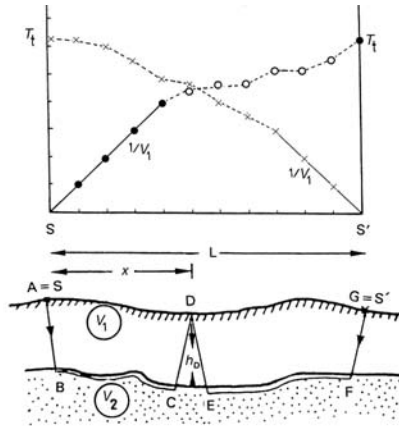
Although the interfaces between real Earth layers are not perfectly flat, head waves still travel along them

Analysis methods:

Best-fit straight line through the points provides some kind of average layer thickness and velocity though the error may be unacceptable

Special analysis techniques:

Phantom arrivals
Delay time
Plus-minus

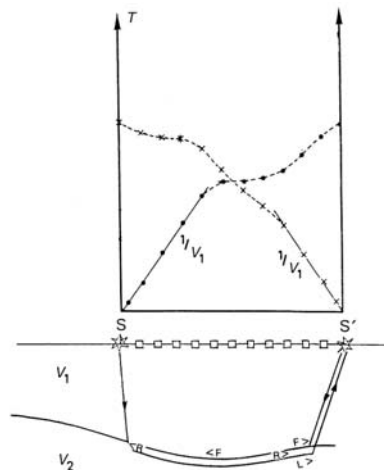


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Phantom arrivals

Undulating surface

- Cannot extrapolate the head wave arrival time curve back to the intercept
- How do we determine layer thickness beneath the shot, S?

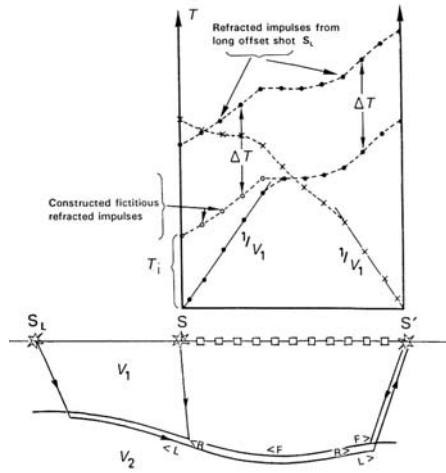


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Phantom arrivals

1. Shoot a long-offset shot, S_L
2. The head wave traveltime curves for both shots will be parallel, offset by time ΔT
3. Subtract ΔT from the S_L arrivals to generate fictitious 2nd layer arrivals close to S – the phantom arrivals
4. The intercept point at S can then be determined: T_i
5. Use the usual formula to determine perpendicular layer thickness beneath S

$$T_i = \frac{2h_s \sqrt{V_2^2 - V_1^2}}{V_2 V_1}$$



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Separation of delay times

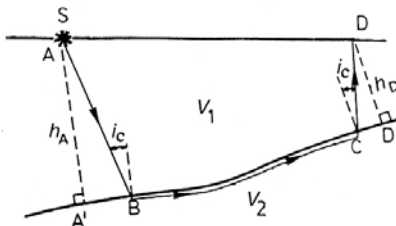
Delay time is the difference between the slant path traveltime (AB) and the traveltime along the refractor beneath (A'B)

Delay time below shotpoint S:

$$\Delta T_S = \frac{AB}{V_1} - \frac{A'B}{V_2}$$

$$\Delta T_S = \frac{h_A}{V_1 \cos i_c} - \frac{h_A \tan i_c}{V_2}$$

$$\Delta T_S = \frac{h_A \sqrt{V_2^2 - V_1^2}}{V_2 V_1}$$



Likewise, beneath D:

$$\Delta T_D = \frac{h_D \sqrt{V_2^2 - V_1^2}}{V_2 V_1}$$

The delay time is related to the perpendicular depth beneath the geophone. If we know the delay time, V_1 and V_2 then we can calculate the depth.

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Separation of delay times

Determining the delay time beneath a geophone, ΔT_D :

Total traveltimes ABFG:

$$T_t = \frac{L}{V_2} + \Delta T_S + \Delta T_{S'}$$

Total traveltimes ABCD:

$$T_{SD} = \frac{x}{V_2} + \Delta T_S + \Delta T_D$$

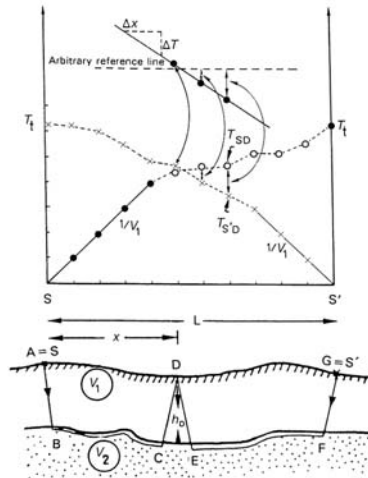
Total traveltimes GFED:

$$T_{S'D} = \frac{L-x}{V_2} + \Delta T_{S'} + \Delta T_D$$

"plus"

Adding the equations for T_{SD} and $T_{S'D}$ and using the equation for T_t we obtain an equation for ΔT_D :

$$\Delta T_D = \frac{T_{SD} + T_{S'D} - T_t}{2} \rightarrow \text{determine } \Delta T_D \text{ from a reversed refraction line}$$



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Separation of delay times

Determining velocity, $V_1 V_2$:

Direct arrival slope = $1/V_1$

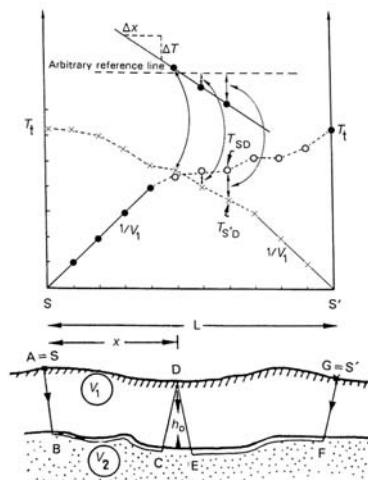
"minus"

Subtracting the equations for T_{SD} and $T_{S'D}$ we obtain the equation:

$$T_{SD} - T_{S'D} = \frac{2x}{V_2} - \frac{L}{V_2} + \Delta T_S - \Delta T_{S'}$$

$$y = ax + b$$

- Plotting $(T_{SD} - T_{S'D})$ against x the slope is $2/V_2$
- Variations in the slope reflect lateral variations in velocity



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The plus-minus method

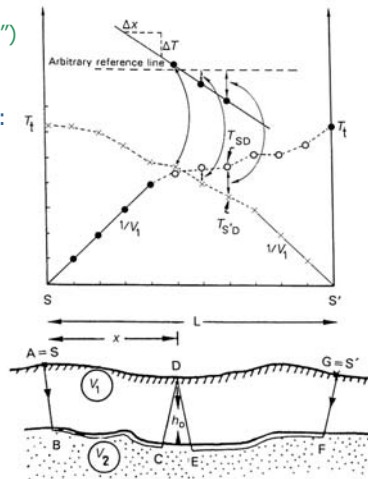
Given the delay time ΔT_D (from the "plus") and the velocities V_1 (from direct arrival) and V_2 (from the "minus")

We can calculate the perpendicular depth:

$$\Delta T_D = \frac{h_D \sqrt{V_2^2 - V_1^2}}{V_2 V_1}$$

Note: we need to see refracted arrivals from both forward and reverse shots (three geophones only in figure)

Use long offset shots to collect necessary data for all geophones



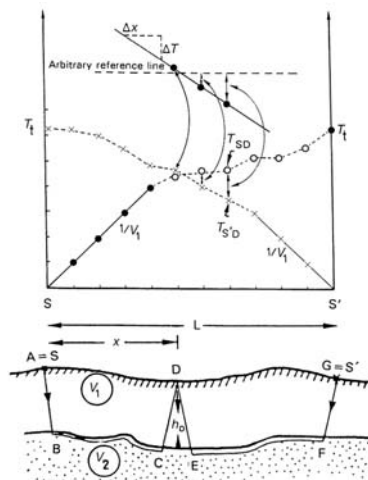
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The plus-minus method

Assumptions and approximations

1. The relief on the refractor must be small compared to the depth
2. Geometric relations assume a small refractor dip (dip < 10 deg)
3. Refractor assumed to be planar between the two points of emergence to a given geophone (ie between C and E)

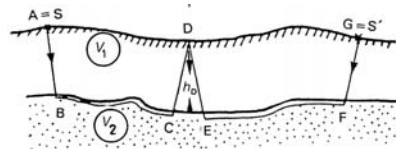
So that ΔT_D is equal when shooting from both sides



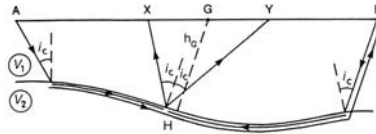
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Generalized reciprocal method

The **plus-minus method** assumes a planar interface and shallow dip between C and E



The **generalized reciprocal approach** uses two geophones, X and Y, recording refracted arrivals originating **from the same point on the refractor** avoiding these assumptions



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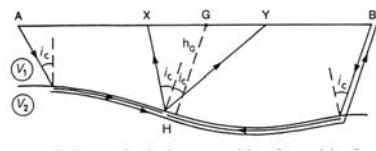
Generalized reciprocal method

Define two functions:

1. Velocity analysis function, T_V

$$T_V = \frac{T_{AY} - T_{BX} + T_{AB}}{2}$$

This is the traveltine from A to H

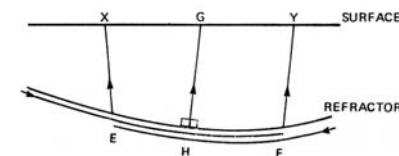


2. Time-depth function, T_G

$$T_G = \frac{T_{AY} + T_{BX} - T_{AB} - (XY/V')}{2}$$

This is the traveltine along EX or FY minus the traveltine of the projection of GX or GY along the refractor interface

i.e. the traveltine along the GH



V' is the apparent refractor velocity determined from T_V

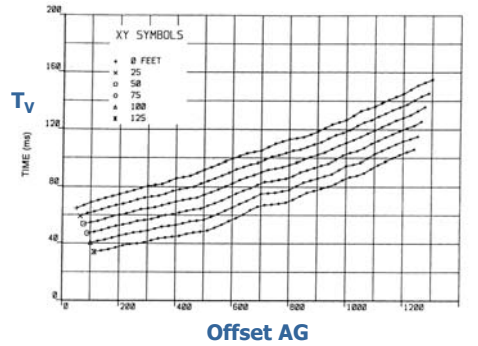
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Generalized reciprocal method

Procedure:

Velocity analysis function, T_V

- Calculate T_V as a function of offset AG for a variety of XY distances
- The optimal XY is when E and F converge on H
- Optimal XY is identified by the smoothest T_V curve
- Refractor velocity V' is the reciprocal of the slope of T_V
- Can determine variations in V' along the length of the profile



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Generalized reciprocal method

Procedure:

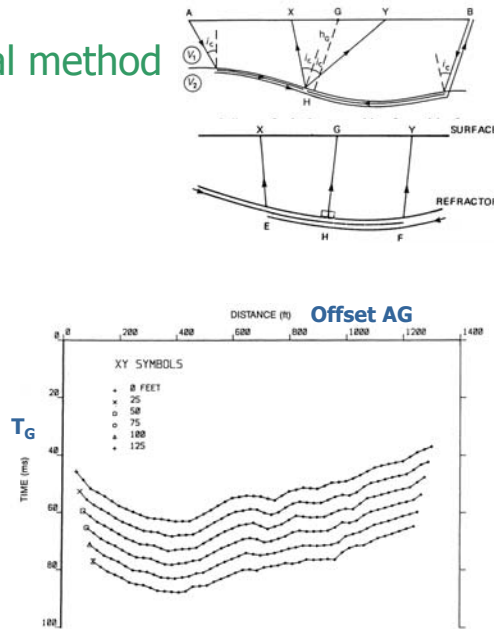
Time-depth function, T_G

- Calculate T_G as a function of offset AG for a variety of XY distances
- Optimal XY is identified by the roughest T_G curve
- Calculate average velocity from surface to refractor

$$\bar{V} = \sqrt{\frac{V'^2 XY}{XY + 2T_G V'}}$$

- Calculate the depth from T_G and the average velocity

$$h = \frac{T_G \bar{V} V'}{\sqrt{V'^2 - \bar{V}^2}}$$



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Experiment design

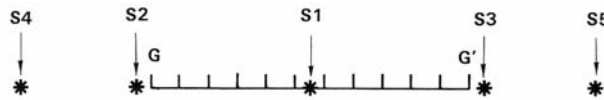
Geophones: often use the same geophones as in reflection work – constraint is the frequency of the geophones

Frequency: refraction studies may be constrained to lower frequencies due to longer ray lengths (10Hz vs. 100Hz for reflection)

Profile length: typically 5 to 10 times the depth of the refractor to ensure head wave as first arrival

Shot points: Typically five for each geophone array

- One at each end: uppermost velocity plus reversed line
- One at center: to determine uppermost layer velocity
- Two long offset shots: to determine phantom arrivals and reverse line



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Limitations

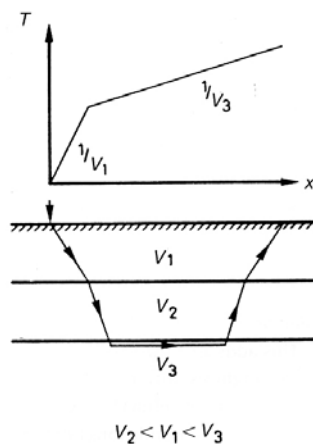
Low velocity layers

- They are completely invisible to the refraction method

- They will cause miss-interpretation of the depth of lower lying layers

The intercept of the refraction from layer 3 will be dependent on the thickness and velocity in layer 2

- Lower layers appear deeper than they are



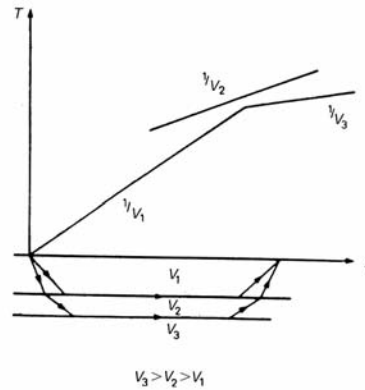
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Limitations Hidden layers

- If a layer is thin it may never produce a first arrival

Either the direct or refraction from a lower (much higher velocity layer) is always first

- Lower layers always appear too shallow as a layer has been missed



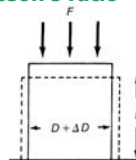
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Velocity and rock strength

Relating velocity to rock strength allows site classification based on refraction studies

1. Elastic moduli:

Poisson's ratio



$$\sigma = \frac{V_P^2 - 2V_S^2}{2(V_P^2 - V_S^2)}$$

$$\sigma = \frac{\Delta D/D}{\Delta L/L}$$

transverse strain
longitudinal strain

- Tells us about the elastic strength of the material
- Important for building foundations etc
- Determined from knowledge of V_P and V_S – need shear sources and horizontal geophones for V_S

2. Degree of jointing

- Jointing lowers seismic velocity
- Degree of jointing can be estimated from velocity for a known rock type

Table 4.2 Empirical relationship between jointing factor (C), seismic velocity (V_p), and the rock quality designation (RQD) of crystalline rocks from northern Sweden. (After Helfrich, 1971)

Degree of separation	C	V_p (m/s)	RQD
Rock without joints	0.65-1	>4500	very good
Rock with few joints	0.45-0.65	4000-4500	good
Rock with joints	0.30-0.45	3500-4000	moderate
Rock with numerous joints	0.15-0.30	3000-3500	bad
Strongly jointed rock	0.00-0.15	<3000	very bad

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Velocity and rock strength

Relating velocity to rock strength allows site classification based on refraction studies

3. Rippability

- Jointing is also a factor in the rippability of a rock
- Seismic velocity can therefore be used to determine the methods necessary to excavate an area

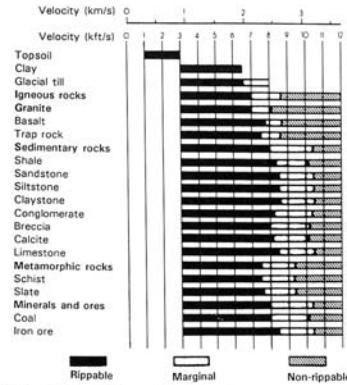


Fig. 4.49 Rippability chart. The ease with which rocks can be ripped by a bulldozer relates to their P-wave velocity. (Courtesy Caterpillar Inc.)