NPTEL ONLINE CERTIFICATION COURSES

EARTHQUAKE SEISMOLOGY

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Module 05 : Refraction and Reflection seismology
Lecture 01: Refraction seismology in flat interfaces and limitations

CONCEPTS COVERED

- Introduction
- Refraction seismology for flat Earth
- Limitations
- Summary

Introduction

Inverse problem

Fundamental data for seismological studies

Travel time of seismic waves

Refraction travel time

Reflection travel time

Information about both the source and properties of the medium

Separation the two and learn about velocity structure between source and receiver

Forward problem

Introduction

- **A major application of seismology is to find the Earth structure, such as the distribution of P- and S-wave velocities and density.**

- **For this purpose, we record arrival times of refracted waves and reflected waves. These travel times are used to infer about the distribution of seismic velocities, and hence elastic properties, within the earth.**

- **We do this utilizing the concepts of refraction and reflection seismology.**

Refraction Seismology

- **More precisely, Refraction seismology is concerned about the travel time of critically refracted wave at the interface of two medium, to identify the depth of interface, velocity of the layer and underlying half space.**

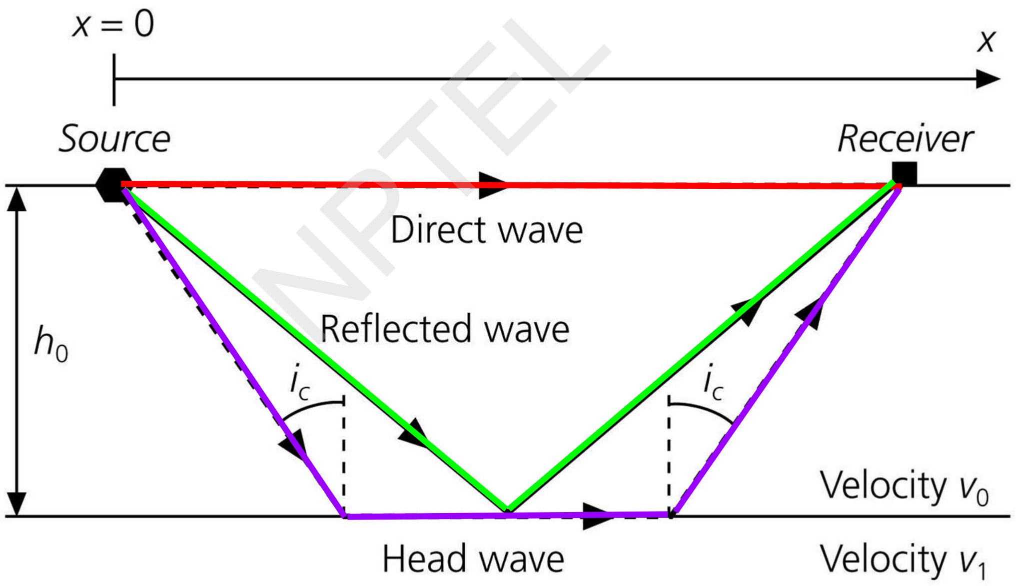
- **Governing Principles:**

  Snell's law

  Huygen's principle

  Fermat principle.

Figure 3.2-1: Ray paths for a layer over a halfspace.



Refraction Seismology (The flat layers Earth model)

Direct wave

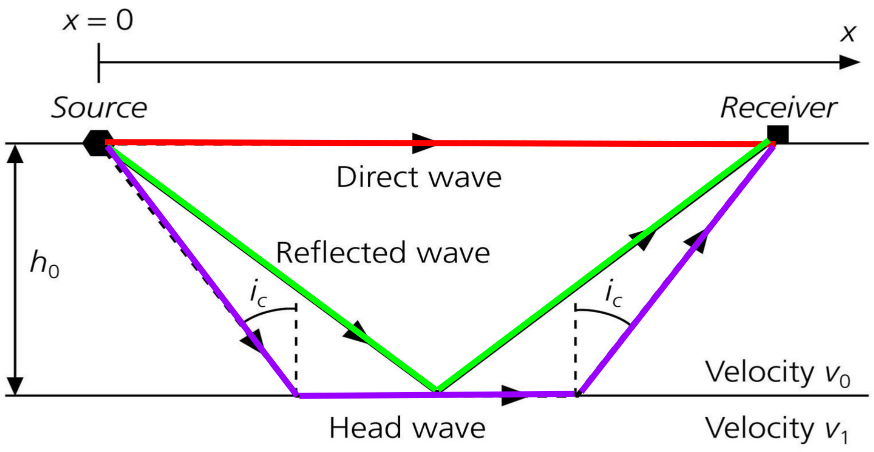
- Distance between source and receiver is called offset.

- Direct wave ray path is shown in red.

$$T_D = \frac{x}{v_0}$$

(This travel time curve is a linear function of distance , with slope $1/v_0$ that goes through the origin.)

Figure 3.2-1: Ray paths for a layer over a halfspace.



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Refraction Seismology

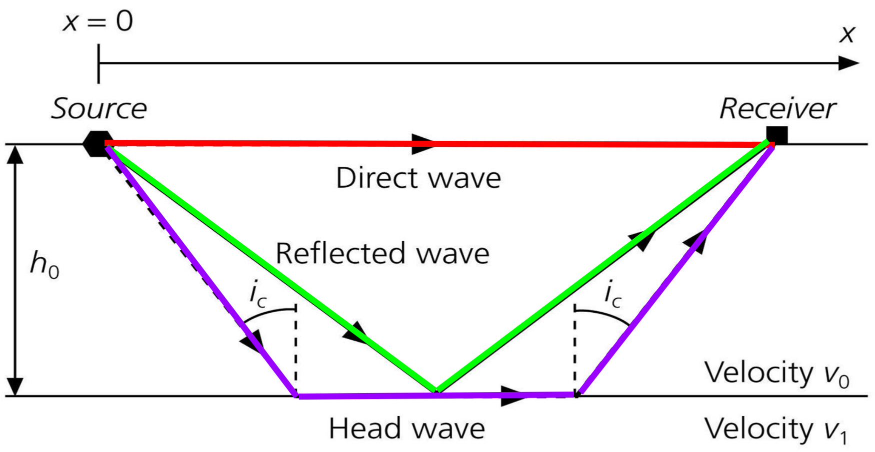
Reflected wave

- The second ray path is for a wave reflected (marked as green) from the interface. Because the angle of incidence and reflection are equal and the wave reflects halfway between the source and receiver.

$$T_R(x) = 2\frac{\left(\frac{x^2}{4} + h_0^2\right)^{\frac{1}{2}}}{v_0} \Rightarrow T_R^2(x) = \frac{x^2}{v_0^2} + 4\frac{h_0^2}{v_0^2}$$

for x>>h

Figure 3.2-1: Ray paths for a layer over a halfspace.



- ➢ This curve is hyperbola in the t-x plane.
- ➢ Reflected wave travel time asymptotically approaches that of direct wave.
- ➢ For zero offset (x=0), the reflected wave path is vertical downgoing and upgoing wave with trave time of: $T_R(0) = 2\frac{h_0}{v_0}$

Refraction Seismology

Head wave

- **The third type of wave is "head wave", often referred to as refracted wave (marked as Purple)**

  In this case, downgoing wave impinges on the interface at an angle at or beyond the critical angle.

$$T_H(x) = \frac{x - 2h_0 \tan i_c}{v_1} + \frac{2h_0}{v_0 \cos i_c}$$
$$= \frac{x}{v_1} + 2h_0\left(\frac{1}{v_0 \cos i_c} - \frac{\tan i_c}{v_1}\right)$$

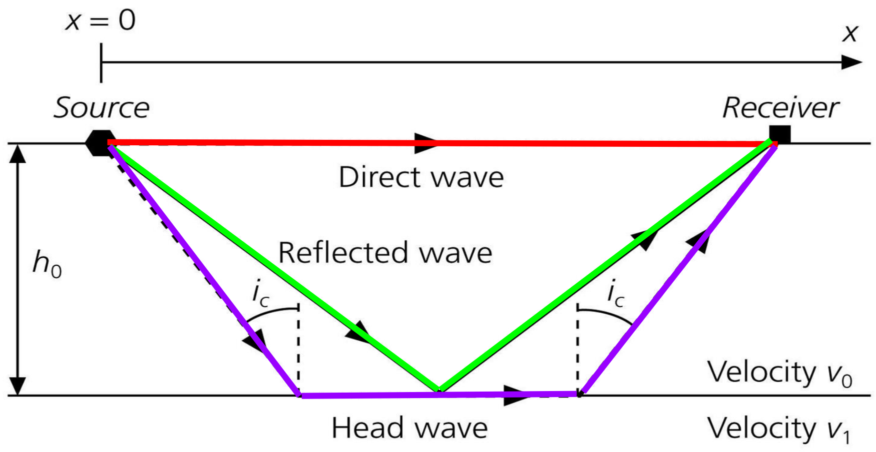
using $\sin i_c = \frac{v_0}{v_1}$

To simplify this equation, we use trigonometric identities showing that

$$\cos i_c = (1 - \sin^2 i_c)^{1/2} = \left(1 - \frac{v_o^2}{v_1^2}\right)^{1/2} \qquad \tan i_c = \frac{\sin i_c}{\cos i_c} = \frac{v_o/v_1}{(1 - v_o^2/v_1^2)^{1/2}}$$

$$T_H(x) = \frac{x}{v_1} + 2h_o\left(\frac{1}{v_o^2} - \frac{1}{v_1^2}\right)^{1/2} = \frac{x}{v_1} + \tau_1$$

Figure 3.2-1: Ray paths for a layer over a halfspace.



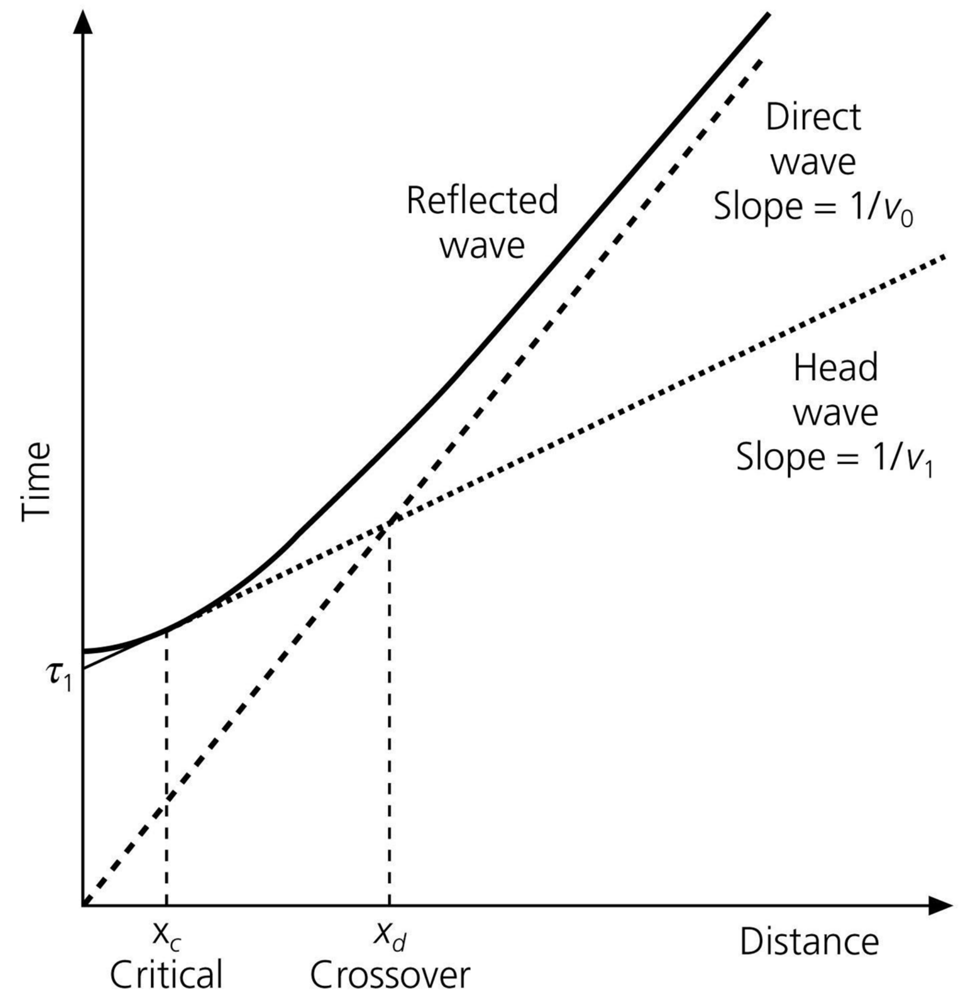
Thus the head wave's travel time curve is a line with a slope of $1/v_1$ and a time axis intercept of

$$\tau_1 = 2h_o\left(\frac{1}{v_o^2} - \frac{1}{v_1^2}\right)^{1/2} \qquad \text{.......equ. 1}$$

- At some point, however, the travel time curves cross the direct wave, and beyond this point the head wave is the first arrival even though it traveled a longer path. This occurs because it travel with greater speed in the underlying layer.

- Although the head wave appears only beyond the critical distance, $x_c = 2h_0 \tan i_c$, where critical incidence first occurs. This arrival is called head wave because after the crossover distance, it reaches before the direct wave.

Figure 3.2-2: Travel time curve for rays in a layer over a halfspace.



The cross over distance is found by setting T_D (x) = T_H (x),

$$x_d = 2h_o\left(\frac{v_1 + v_o}{v_1 - v_o}\right)^{1/2} \qquad \text{.......equ. 2}$$

Hence the crossover distance depends on the velocities of the layer and the half space and the thickness of the layer.

Note:

1. **Slope of direct wave gives v_0, velocity of top layer.**
1. **Slope of head wave gives v_1, velocity of half space.**

For n-layers

The travel time curve for a head wave at the top of the n^{th} layer is a line with slope $1/v_n$, that can be extrapolated to its intercept on the t axis, τ_n , and written

$$T_{H_n}(x) = \frac{x}{v_n} + \tau_n$$

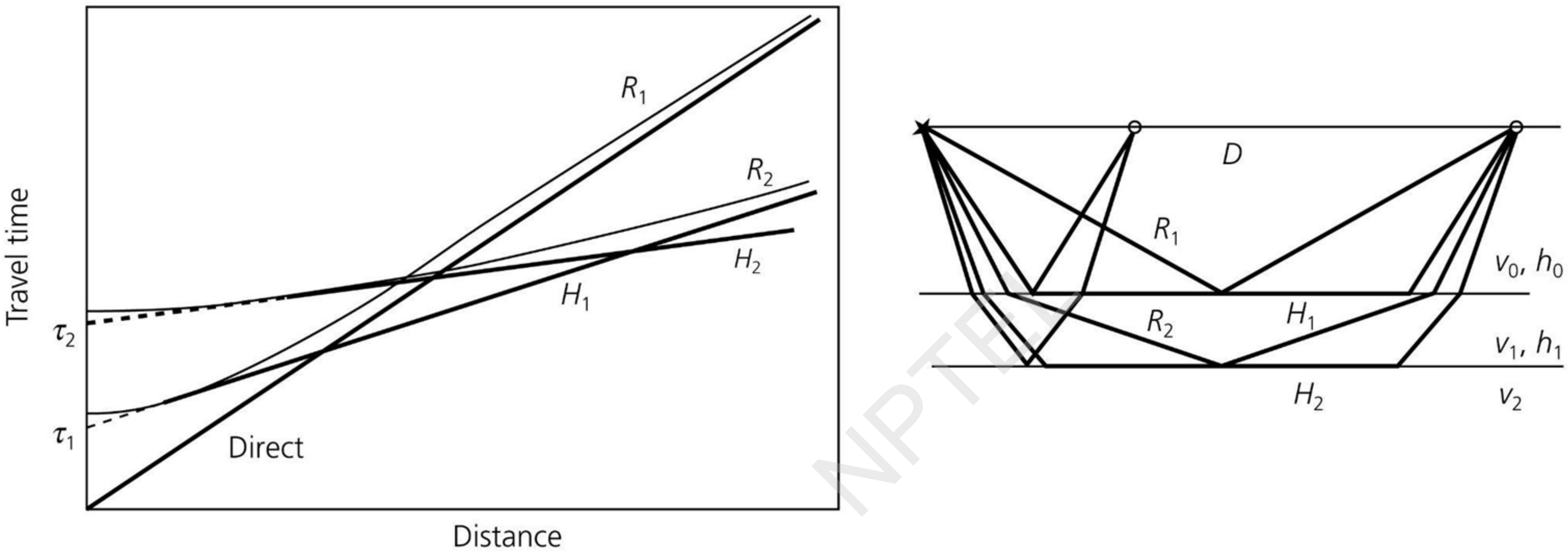
where, by analogy to the layer over the half-space case

$$\tau_n = 2\sum_{j=0}^{n-1} h_i \left(\frac{1}{v_j^2} - \frac{1}{v_n^2}\right)^{1/2}$$

The thickness of successive layers can be found by starting with the top layer, whose thickness h_0, is given by Eqn 1 or 2, and continuing downward using the iterative formula:

$$h_{n-1} = \frac{\tau_n - 2\sum_{j=0}^{n-2} h_i \left(\frac{1}{v_j^2} - \frac{1}{v_n^2}\right)^{1/2}}{2\left(\frac{1}{v_{n-1}^2} - \frac{1}{v_n^2}\right)^{1/2}}$$

Figure 3.2-7: Rays and times for two layers over a halfspace.

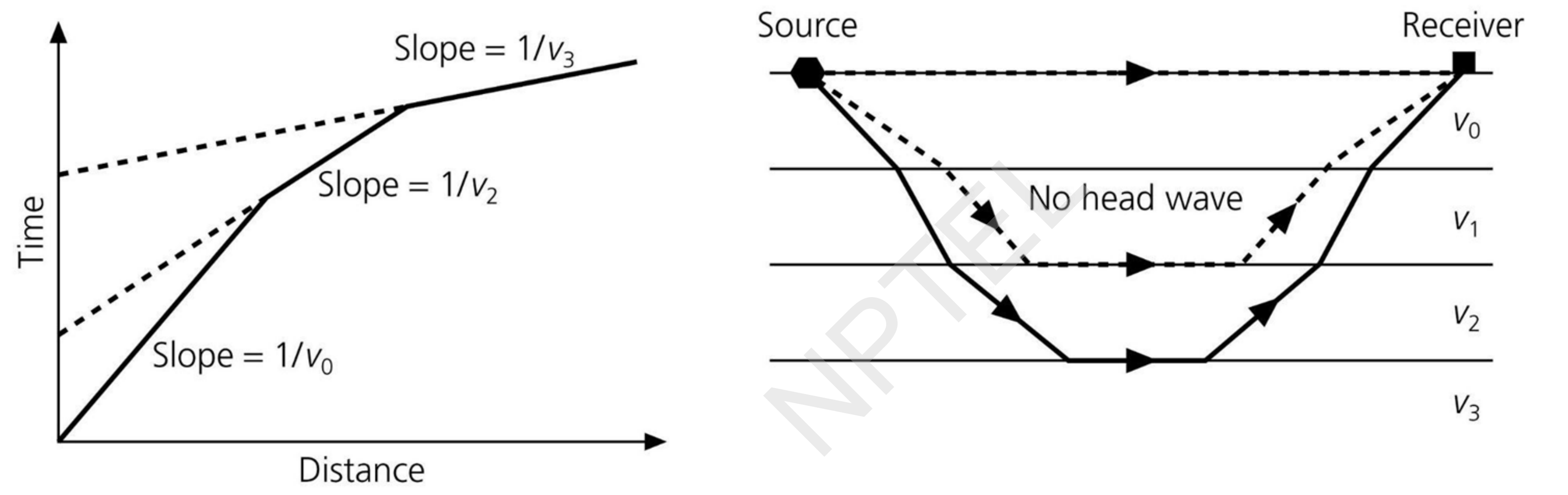


Ray paths and travel times for a multilayered model in which velocity increases with depth. Each layer gives rise to a head wave H_i , whose intercept on the time axis is τ_i , and a reflection R_i . The direct wave arrival is also shown.

Limitations

Case 1: Presence of low velocity zone

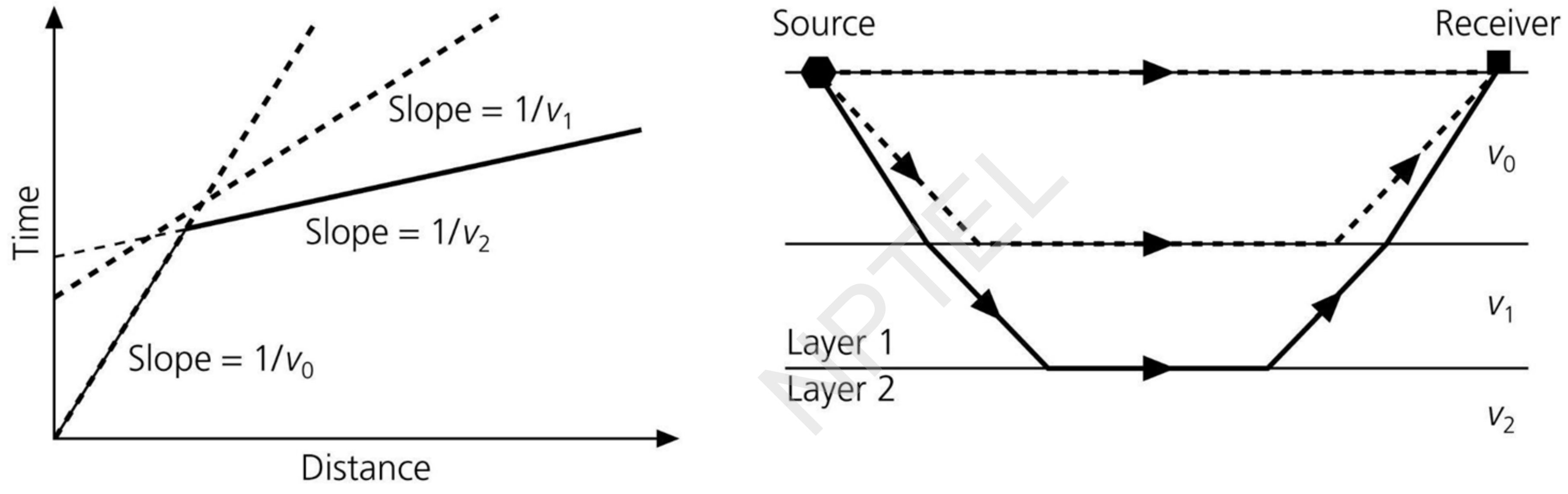
Figure 3.2-8: Rays and times for the case with a low-velocity layer.



Travel time curves, showing first arrivals only, for a model with three layers over a halfspace. Because the middle layer is a low-velocity layer with $v_1 < v_0$, no head wave arises at its top.

Case 2: Layer is too thin or has a small velocity contrast

Figure 3.2-9: Rays and times for the case of a"blind zone."



Another possible problem occurs if a layer is thin or has a small velocity contrast with the one below it. Although a head wave results, it may never appear

Summary

- A major application of seismology is the determination of the distribution of seismic velocities, and hence elastic properties, within the earth.
- Refraction seismology is concerned about the travel time of critically refracted wave at the interface of two medium, to identify the depth of interface, velocity of the layer and underlying half space.
- Travel time as a function of offset $T_D = x/v_0$

$$T_R^2(x) = \frac{x^2}{v_0^2} + 4\frac{h_0^2}{v_0^2}$$

$$u = \sqrt{p^2 + \eta^2}$$

$$T_H(x) = \frac{x}{v_1} + 2h_o\left(\frac{1}{v_o^2} - \frac{1}{v_1^2}\right)^{1/2} = \frac{x}{v_1} + \tau_1$$

- The thickness of successive layers can be found by starting with the top layer:

$$h_{n-1} = \frac{\tau_n - 2\sum_{j=0}^{n-2} h_i\left(\frac{1}{v_j^2} - \frac{1}{v_n^2}\right)^{1/2}}{2\left(\frac{1}{v_{n-1}^2} - \frac{1}{v_n^2}\right)^{1/2}}$$

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- Seismology course, Professor Derek Schutt, Colorado State Univ., USA.

THANK YOU !