

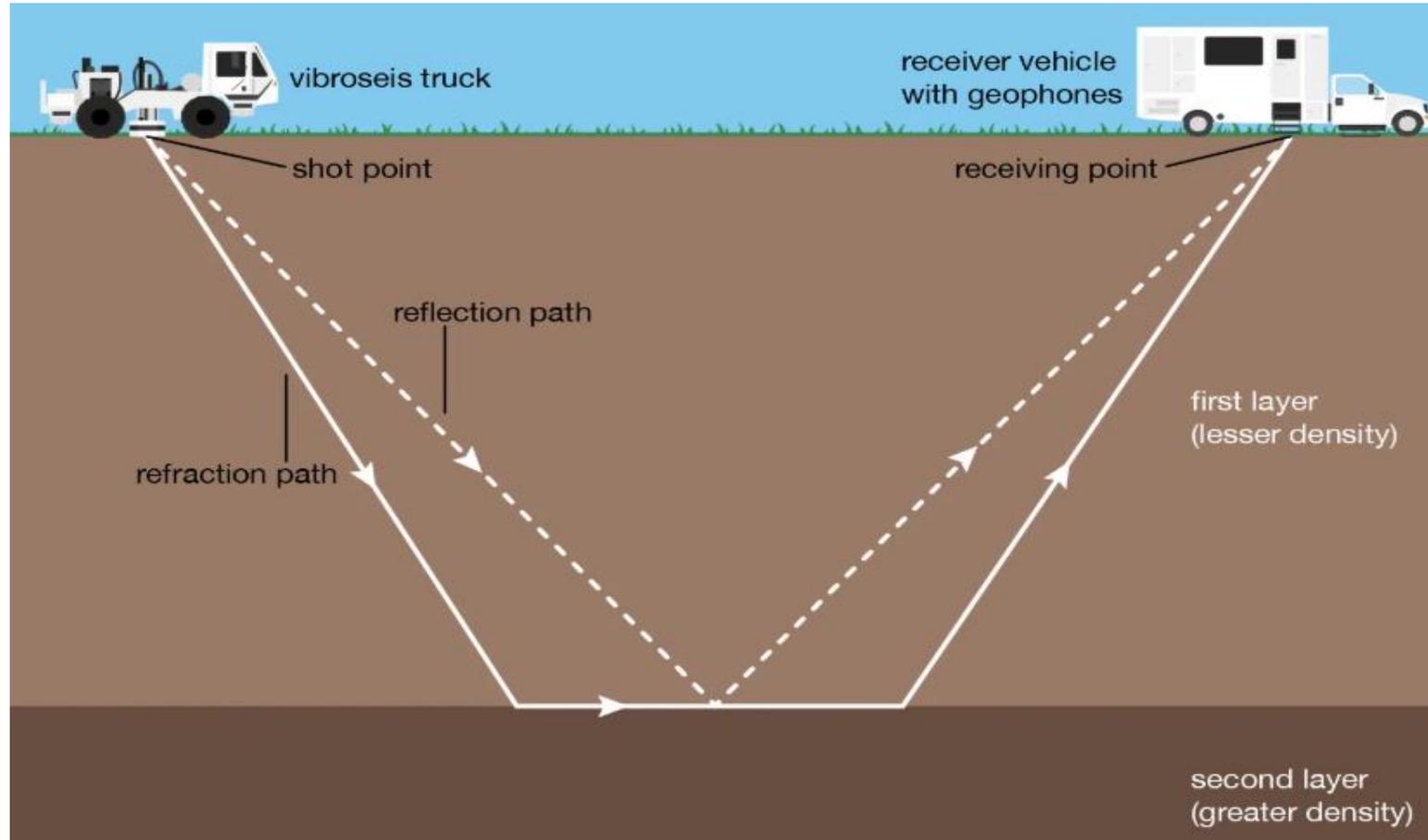


# Chap III: Seismic ( Shallow seismic) methods used in Hydrogeology

- **Generalities about Seismic Methods (Shallow):** in hydrogeology are geophysical techniques that use the propagation of artificially generated **seismic waves** through the ground due to elastic deformation to image and examine sedimentology and stratigraphy, that will give an image of subsurface structure. They are detecting geologic faults, evaluating karst (soluble rocks) conditions, mapping the top of bedrock, measuring the depth to the water table and mapping hydrogeological features.
- **How seismic methods works:** To conduct a seismic survey, you need a sources of seismic energy such as hammer, weight drop, explosive, or vibroseis are used to create and send mechanical waves into the subsurface considered at the source of the transmitted wave. This elastic wave is received by specialized microphone in the ground known as **geophone** which will be recorded and its physical feature in a sismograph.



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**Figure 9: Seismic survey using vibroseis truck ( Refraction and Reflection)**

**Source:** <https://www.britannica.com/science/seismic-survey>

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Jijel university Academic Year 2025\_2026



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**Seismic waves propagation:** includes **Body waves**, which travel 3D through solid volumes, and **Surface waves**, which travel near the surface of the ground where they propagate. **Body waves** include **P-waves** ( primary waves) and **S-waves** ( Shear waves).

**The P-waves( $V_p$ )** are compressional sound waves they are very fast and they are the first waves recorded on the seismograms; they are strongly influenced by saturation, porosity, and lithology. P-waves velocity are in dry > partially saturated > fully saturated (due to fluid incompressibility).

**The S-waves ( $V_s$ )** are distortional, their speed is 40–60% of P-waves velocity. They are used in geotechnical, particularly between boreholes, to determine the shear modulus of soils and foundation materials and in hydrogeology they are **not affected by fluids** (only **matrix** and **porosity**).

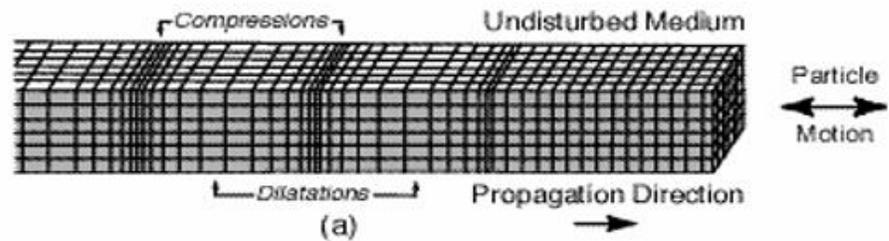
**Surface waves** are able to travel only within a few seismic wavelengths of the surface of a solid. They are compounded of Love waves and Rayleigh waves.

See, figure 10 to understand physical differences between these type of waves.

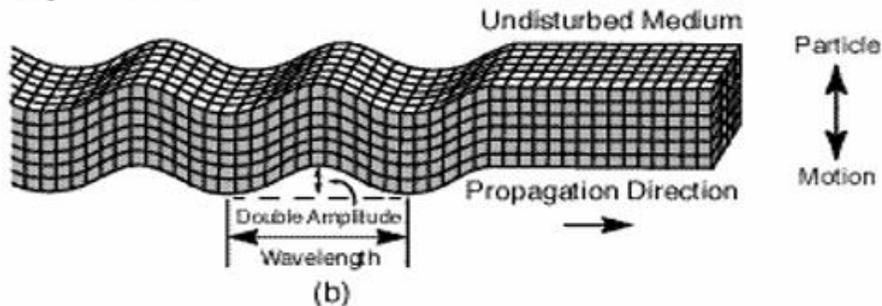


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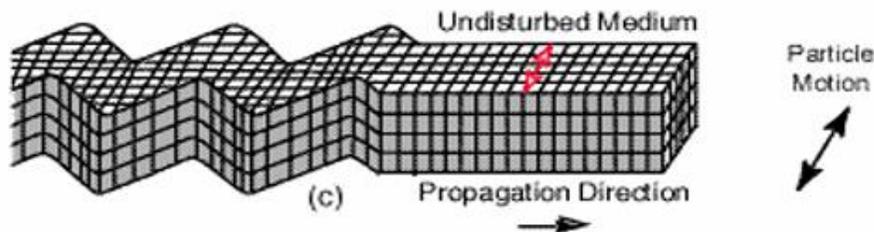
P-Wave



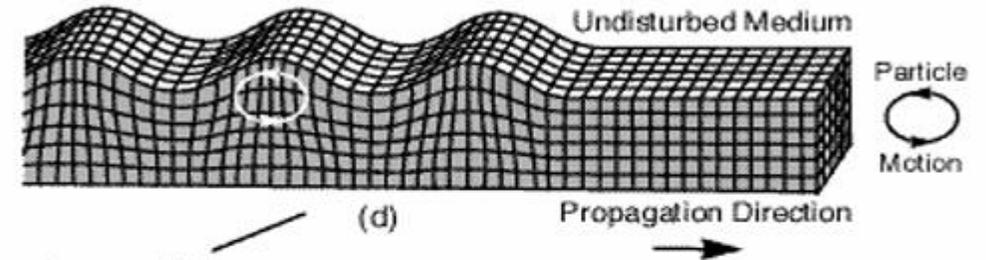
$S_V$ -Wave



$S_H$ -Wave



Rayleigh Wave



Love Wave

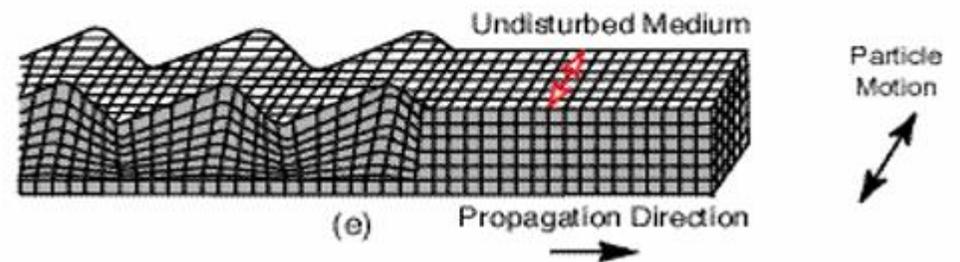


Figure 10: Body waves (left) traveling in a solid medium and Surface waves (right) traveling along a section of earth surface.

Source: Rubin & Hubbard – Hydrogeophysics (2005)



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**Waves attenuation** can provide information about the hardness or rigidity of the soil formation (material) traversed by the waves. P-waves attenuate faster in unsaturated soils formation than in saturated soils formation, whereas S-wave attenuation usually is not highly affected by the degree of saturation.

When the velocity of the wave and the shotpoint (Source of wave) and receiver locations are known for several of the geophones, the seismologist can determine how deeply the wave has penetrated and whether it has been refracted, reflected as it traversed its underground pathway. This information is useful to determine the depth to bedrock.

**Table 3: Seismic velocities of different material and soil formation Daly R.A 1966**

<i>Medium</i>	<i>P-Wave Velocity (m/s)<sup>p</sup></i>	<i>S-Wave Velocity (V<sub>s</sub>) (m/s)<sup>s</sup></i>	<i>Density (ρ) (g/cm<sup>3</sup>)<sup>f</sup></i>
<i>Air</i>	<i>335</i>	<i>0</i>	<i>0</i>
<i>Soil</i>	<i>100 - 600</i>	<i>-</i>	<i>1.6</i>
<i>Dry sand, gravel</i>	<i>200 - 1000</i>	<i>400</i>	<i>1.6</i>
<i>Wet sand, gravel</i>	<i>600 - 1800</i>	<i>500</i>	<i>1.9</i>
<i>Clay</i>	<i>1000 - 2200</i>	<i>-</i>	<i>1.5</i>
<i>Till</i>	<i>1600 - 2200</i>	<i>-</i>	<i>1.7</i>
<i>Water</i>	<i>1500 - 1600</i>	<i>0</i>	<i>1.0</i>
<i>Solid rock</i>	<i>1600 - 6500</i>	<i>-</i>	<i>2.3 - 2.8</i>

**The velocity ratio:  $V_p/V_s$**  is a seismic parameter used to analyze subsurface rock and fluid properties.

- a higher ratio can indicate fluids like water or magma, while a lower ratio might suggest dry steam or gas.
- to distinguish between different rock types, like carbonates and shales, as their elastic properties vary.
- significantly increase of this ratio making it useful for predicting pore pressure.



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**Seismic techniques:** As already explained it is an image construction of the subsurface, primarily employing **seismic refraction** and **reflection** to map geological layers, locate the water table, and identify features like bedrock depth, and faults. **They are non-destructive, cost-effective for large areas compared to drilling wells.**

**Seismic refraction:** studies are mainly based on analysing the travel times of waves refracted/bent (broken) at boundaries between different geological layers. **Often, only first arrival times are picked from the seismograms (see Fig 11)** which can be easily identified. A lot of algorithms are in use to convert the observed travel time-distance functions into cross-sections of the subsurface. These cross-sections show the seismic velocity structure comprising the depth of seismic interfaces and the velocity inside layers. It gives a final product; the Seismic refraction tomography map see Fig-12.

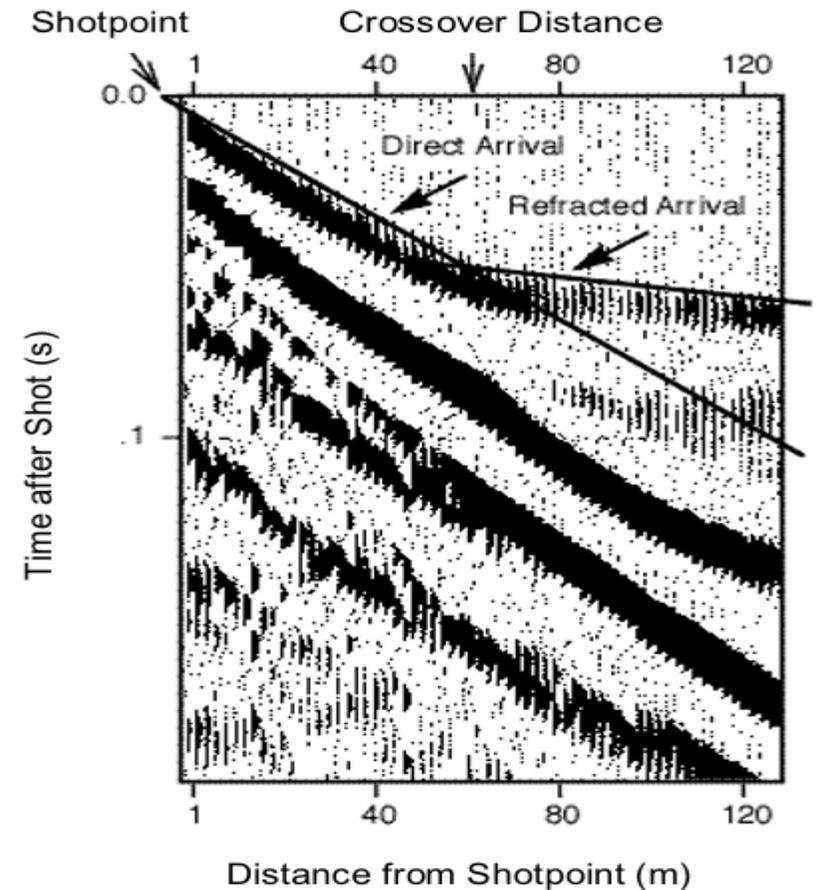
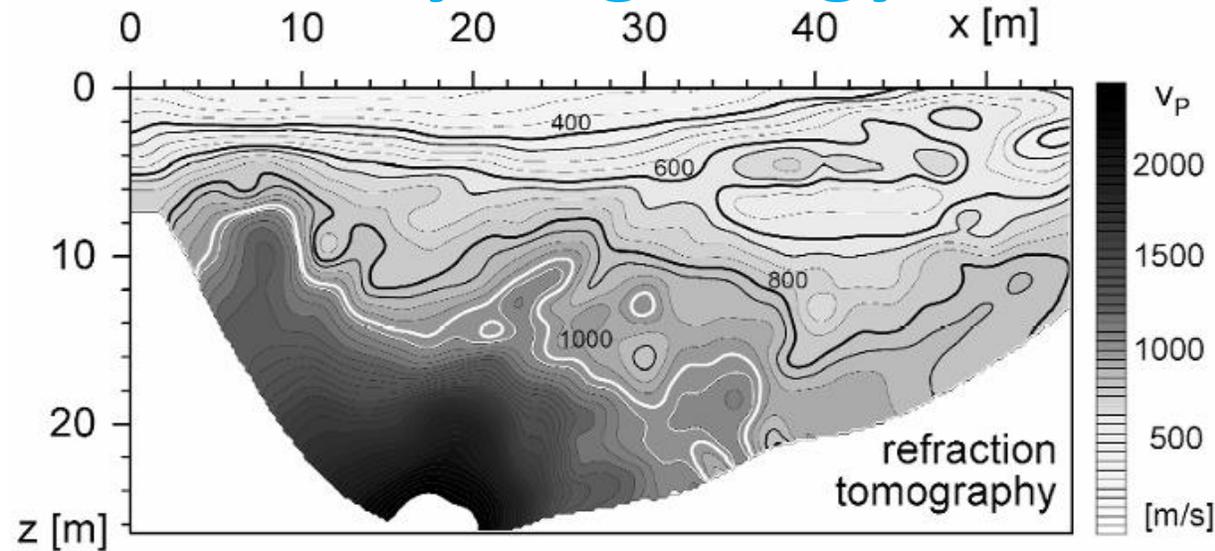


Figure 11: Refraction Seismogram for the 2 layers case  
Source: Rubin & Hubbard – Hydrogeophysics (2005)



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**Figure-12: Seismic refraction tomography map based on P waves . (Source: Ground water geophysics R.Kirsch 2ed 2009)**

Refraction tomography map provides a detailed image of the subsurface velocity structure, which can be interpreted to determine:

- **Depth and shape of bedrock:** Bedrock typically has a much higher seismic velocity than overlaying formation soil.
- **Subsurface layer properties:** unconsolidated soil, compacted sand, competent rock, or fractured.
- **Geological structures:** Faults, paleochannels ( old inactive river filled with younger sediment ), and other discontinuities that can be identified by abrupt changes in velocity.
- **Geotechnical parameters:** it gives rock density, porosity, and elastic moduli (e.g., Young's and bulk moduli).



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There are several methods to interpret seismic refraction waves such as:

Intercept-Time Method (ITM);

Reciprocal Method (RM), Hawkins (1961);

Generalized Reciprocal Method (GRM);

Plus-Minus Method of Hagedoorn (1959), similar to the reciprocal method;

**E.g.** Using ITM method to interpret refraction waves and based on trigonometry and geometry we can have the following equations:

$$z = \frac{x_{\text{cros}}}{2} \sqrt{\frac{V_1 - V_0}{V_1 + V_0}}$$

Where: **Z** the depth to the interface in a two-layer seismic refraction model

**Xcrit** The distance at which refracted rays are first physically possible

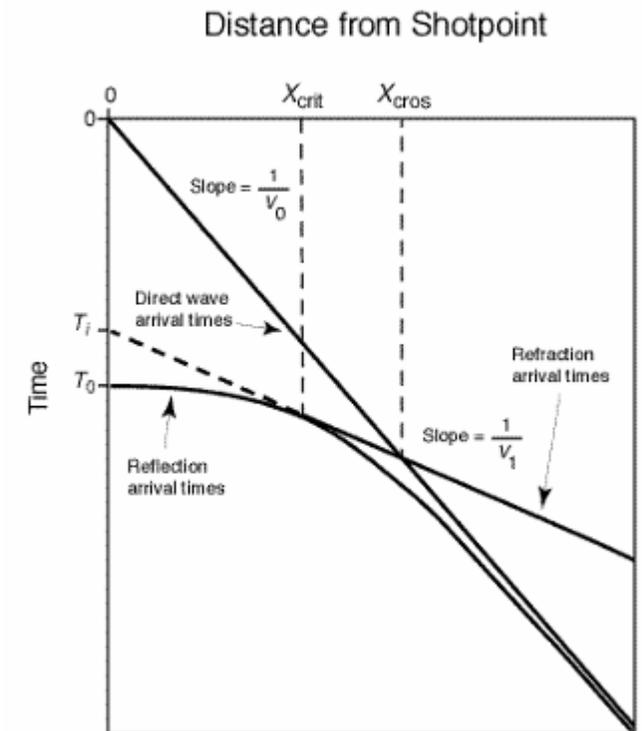
**Xcros** The distance at which the direct and refracted rays arrive simultaneously

**To** The reflection time of a normal-incidence P-wave reflection traveling vertically to and from the top of the substrate.

**T1** is the zero-offset distance intercept time of a line drawn through the first-arriving refracted P-waves

**Vo** velocity of the direct arrival wave

**V1** velocity of the refracted arrival wave





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## Intercept-Time Method ( ITM) application example:

A seismic refraction survey is conducted to determine the depth to the water table in a two-layer system: a dry sand layer (P-wave velocity  $V_1=500$  m/s) over a saturated sand layer (P-wave velocity  $V_2=1800$  m/s). The critical distance is 10 meters, and the crossover distance is 20 meters.

- Calculate the depth to the water table.
- What does the crossover distance indicate?
- How would a fractured bedrock layer beneath the saturated sand affect the results?

## Solution:

The depth to the interface in a two-layer seismic refraction model is given by:

$$Z = X_{\text{cross}}/2 \sqrt{(V_2 - V_1)/(V_2 + V_1)}$$

where  $X_{\text{cross}}=20$  m is the crossover distance,  $V_1=500$  m/s and  $V_2=1800$  m/s

Calculate:  $V_2 - V_1 / V_2 + V_1 = 1800 - 500 / 1800 + 500 \approx 0.5652$  .

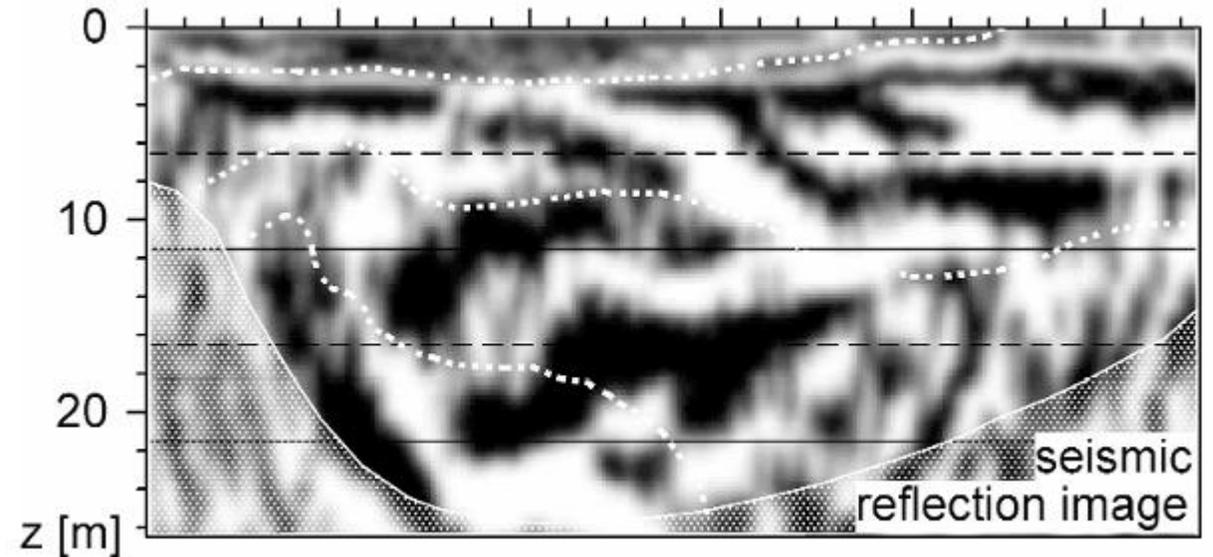
$$\sqrt{0.5662} \approx 0.7518$$

$Z = 10 \times 0.7518 = 7.518$  m. The depth to the water table is approximately **7.52 m**.



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**Seismic reflection:** Often, the shallow seismic reflection method is used to map geologic structure and stratigraphy because *it offers greater detail than* the seismic refraction method (Don W, Steeples in Rubbin & Hubbard 2005). It has been used increasingly since 1980 in applications at shallow depths, to map bedrock elevation, map water table, locating stratigraphic pinch outs, and detect shallow faults. Reflection method is capable of producing detailed 3D images of the earth's interior at the resolution of a seismic wavelength and define where in the earth the elastic moduli and mass densities change.



**Fig 13 : Corresponding seismic reflection section ( to Fig 12) showing the complex layering within the vadoze zone. Velocity contours for  $v_P = 400, 800$  and  $1200$  m/s are indicated by dashed lines for comparison (by courtesy of GeoExpert AG, Schwerzenbach, Switzerland)**

**vadoze zone: Non saturated zone in the aquifer.**



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**Table 4: Summary Table: Seismic Methods in Hydrogeology**

Method	Depth Range	Resolution	Hydro related Parameters	Best For
Refraction	5–50 m	Low–Medium	Water table, paleochannel detection, layer velocity, porosity	Layered aquifers
Reflection	10–500 m	High	Water table , Aquifer geometry, faults, porosity	Structural mapping