Geophysical Methods

There are several types of geophysical tests that can be used for:

1. Determination of the stratigraphy of a site
2. Identification of abrupt change in soil or rock formation
3. Measuring of dynamic parameters in situ
4. Identification of cavities in study region
5. Identification of underground obstruction

- Geophysical tests include mechanical waves and electromagnetic techniques.

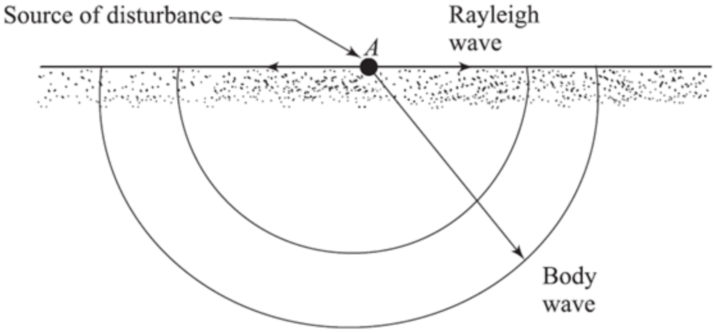
i. Mechanical waves techniques include seismic refraction surveyes, crosshole, downhole, and spectral analysis of surface wave test. These tests are useful in determination of the elastic properties of the subsurface media and small shear modulus.

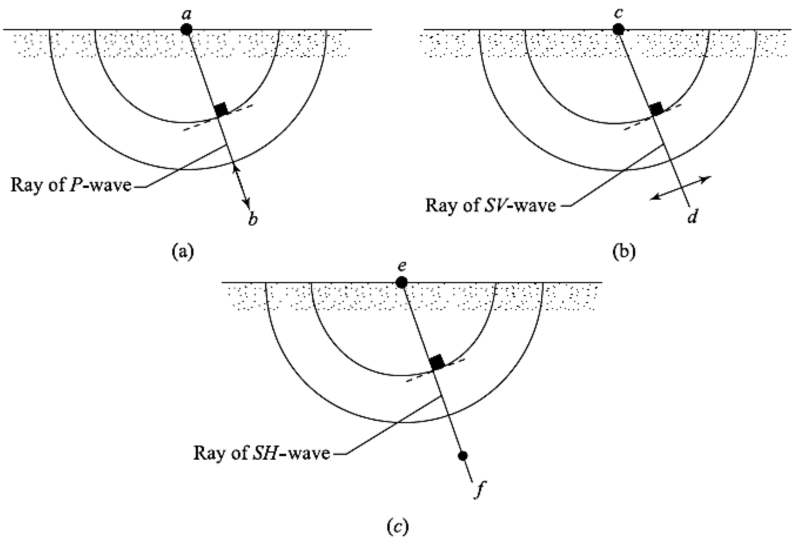
ii. Electromagnetic techniques include resistivity, EM, magnetometer, and radar.

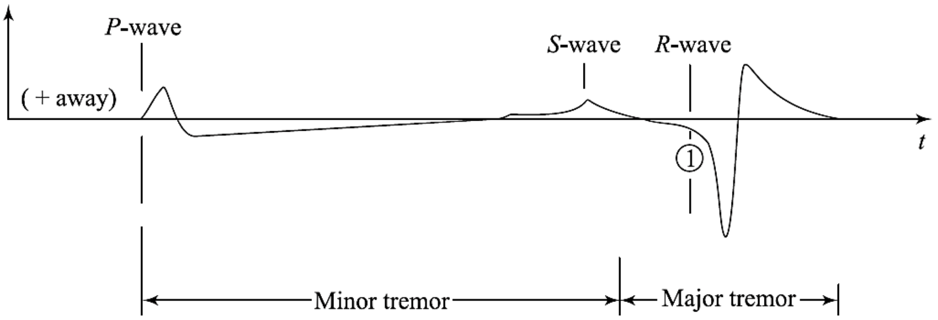
1. Mechanical Waves Techniques

Utilizing the propagation of waves at their characteristics velocities for determining layering, elastic stiffness, and damping parameters.

- Conducted at very small strain levels ($\varepsilon \approx 10^{-3}\%$), i.e. elastic region of soil.
- There are four basic wave forms generated within a semi-infinite elastic half space:
  a. Compression wave (P-wave)
  b. Shear wave (S-wave)
  c. Surface or Rayleigh wave (R-wave)
  d. Love wave (L-wave)
- The P-wave an S-wave are termed to the body waves and most commonly used in geotechnical engineering.
- The R-wave and L-wave are special types of hybrid compression /shear waves that occur at the ground surface boundary (R) and soil layer interface (L).





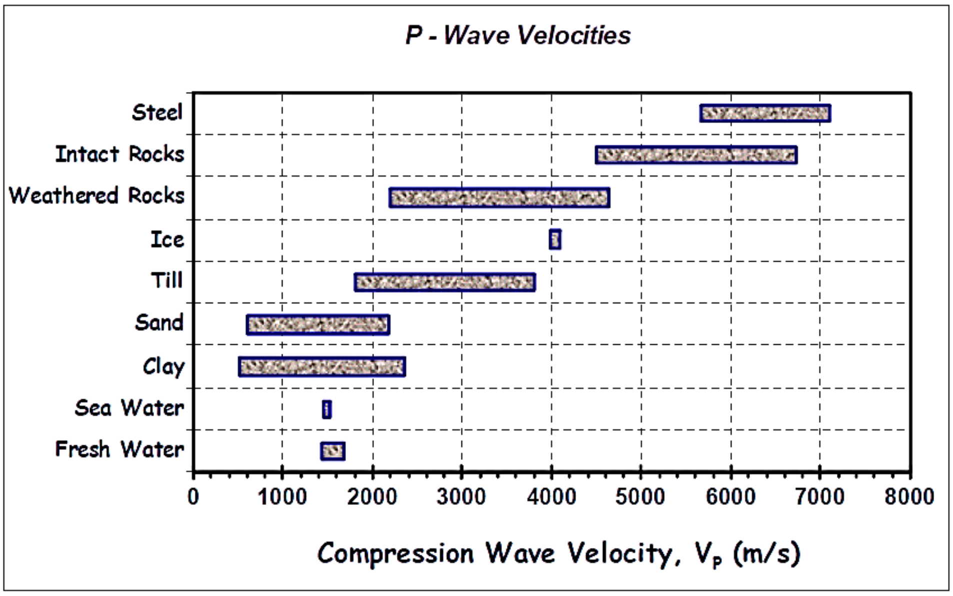


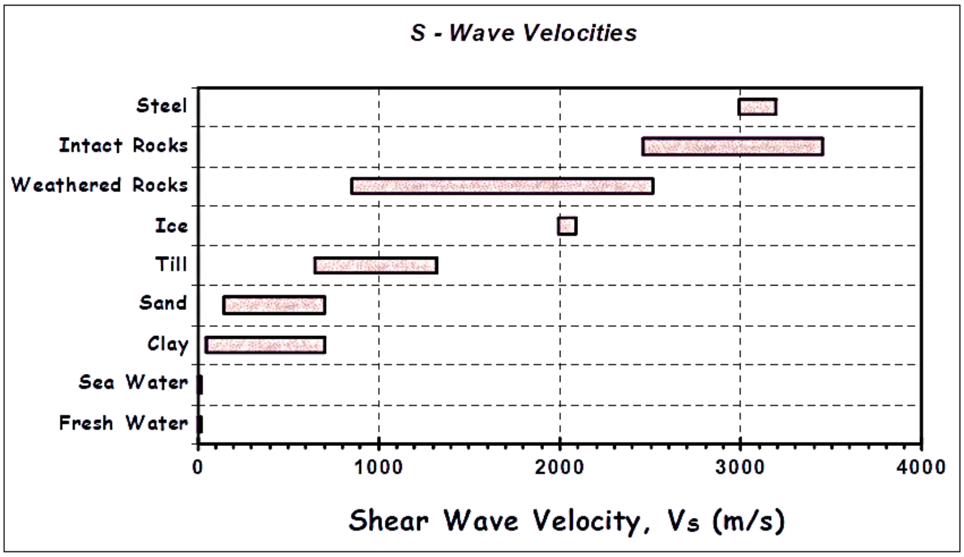
- The compression wave velocity $(v_p)$is the faster wave and moves as an expanding spherical front that emanates from the source.
  - The magnitude of v_p for the soil is $400\ m/sec \leq v_p \leq 2500\ m/sec.$
  - In rocks: $2000\ m/sec \leq v_p \leq 7000\ m/sec.$
  - In water: $v_p = 1500\ m/sec.$
- The shear wave velocity (v_s) is the second faster wave and expands as cylindrical front having localized motion perpendicular to the direction of travel.
  - The magnitude of v_s for soils is $100\ m/sec \leq v_s \leq 600\ m/sec.$
  - Since water cannot sustain shear forces, it has no shear wave and therefore does not interfere with v_s measurements in soils and rocks.

In geomechanics, the shear wave is the most important since it relatives directly to the shear modulus. The small-strain shear modulus $(G_{max}\ or\ G_0)$ is evaluated from the expression:

$$G_0 = \rho_T\ v_s^2$$

Where: ρ_T =total density of soil

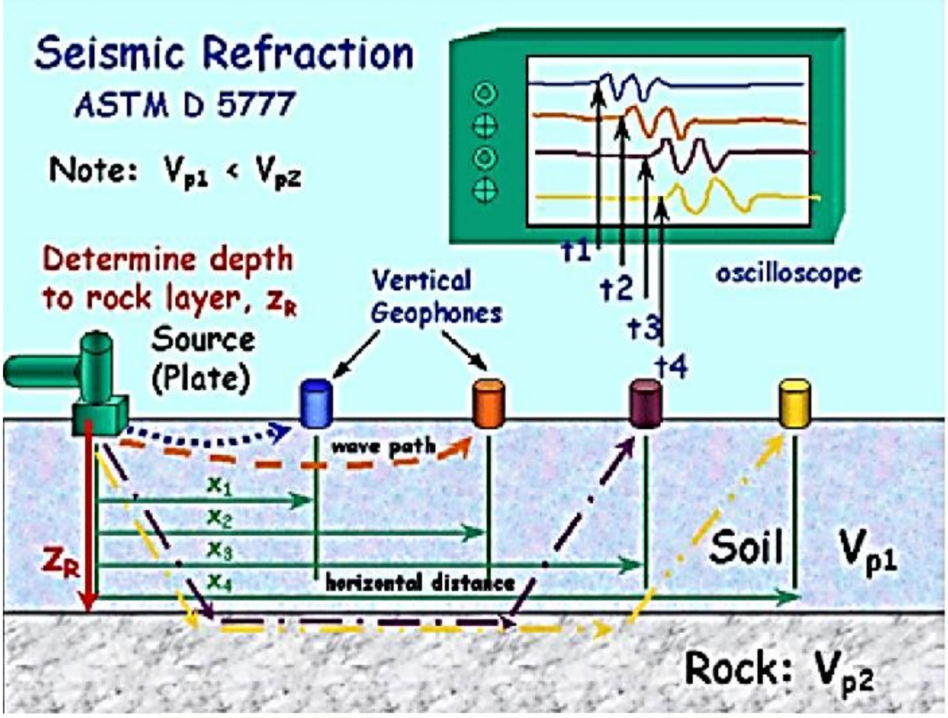


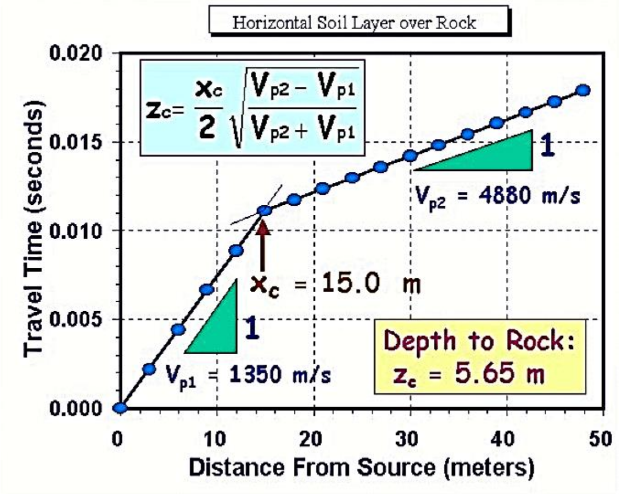


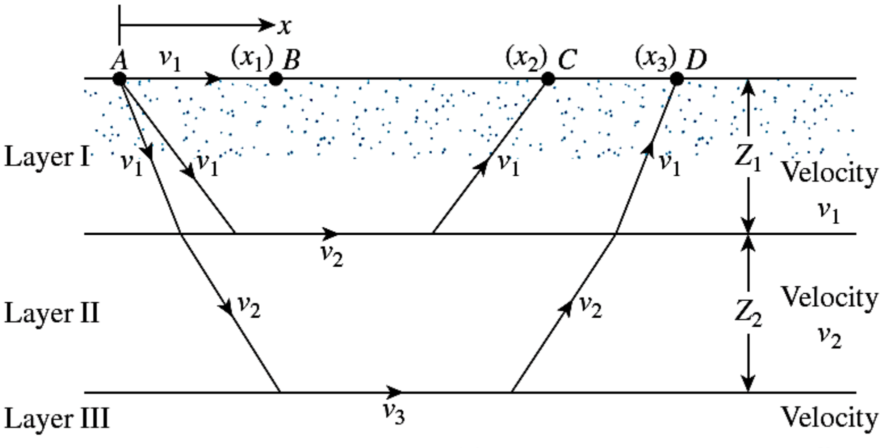
Seismic Refraction (SR)

Seismic refraction is used for the determining the depth to the very hard layers such as bedrocks.

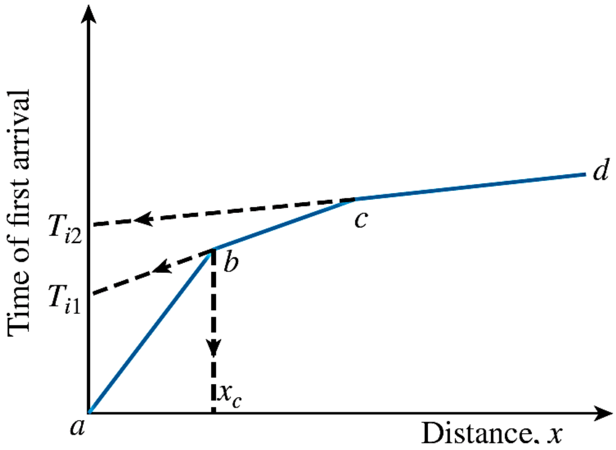
- Designated in ASTM D5777
- The procedure involves as mapping of v_p arrivals using a linear array of geophone across the site.
- Generally, a single geophone can be used by moving the geophone position and repeating the source event.


Seismic Refraction
ASTM D 5777
Note: Vp1 < Vp2
Determine depth to rock layer, zR
Source (Plate)
Vertical Geophones
t1
t2
t3
t4
oscilloscope
wave path
x1
x2
x3
x4
horizontal distance
ZR
Soil
Vp1
Rock: Vp2


Horizontal Soil Layer over Rock
Travel Time (seconds)
0.020
0.015
0.010
0.005
0.000
0
10
20
30
40
50
Distance From Source (meters)
zc = (xc/2) √((Vp2 − Vp1)/(Vp2 + Vp1))
1
Vp2 = 4880 m/s
xc = 15.0 m
1
Vp1 = 1350 m/s
Depth to Rock:
zc = 5.65 m


x
A
v1
(x1) B
(x2) C
(x3) D
Layer I
v1
v1
v1
v1
Z1
Velocity
v1
v2
Layer II
v2
v2
Z2
Velocity
v2
Layer III
v3
Velocity
v3

(a)



First arrival of disturbance waves will be related to the velocities of the P waves in various layers. The velocity of P waves in a medium is

$$v = \sqrt{\frac{E_s}{\left(\frac{\gamma}{g}\right)} \frac{(1-\mu_s)}{(1-2\mu_s)(1+\mu_s)}}$$

where

E_s = modulus of elasticity of the medium
γ = unit weight of the medium
g = acceleration due to gravity
μ_s = Poisson's ratio

To determine the velocity v of P waves in various layers and the thicknesses of those layers, we use the following procedure:

Step 1. Obtain the times of first arrival, t_1, t_2, t_3, … , at various distances x_1, x_2, x_3, … from the point of impact,

Step 2. Plot a graph of time t against distance x. The graph will look like the one shown in Figure,

Step 3. Determine the slopes of the lines ab, bc, cd, … :

$$\text{Slope of } ab = \frac{1}{v_1}$$

$$\text{Slope of } bc = \frac{1}{v_2}$$

$$\text{Slope of } cd = \frac{1}{v_3}$$

Here, v_1, v_2, v_3, … are the P-wave velocities in layers I, II, III, … , respectively,

Step 4. Determine the thickness of the top layer:

$$Z_1 = \frac{1}{2}\sqrt{\frac{v_2 - v_1}{v_2 + v_1}}\, x_c$$

The value of x_c can be obtained from the plot, as shown in Figure.

Step 5. Determine the thickness of the second layer:

$$Z_2 = \frac{1}{2}\left[T_{i2} - 2Z_1\frac{\sqrt{v_3^2 - v_1^2}}{v_3 v_1}\right]\frac{v_3 v_2}{\sqrt{v_3^2 - v_2^2}}$$

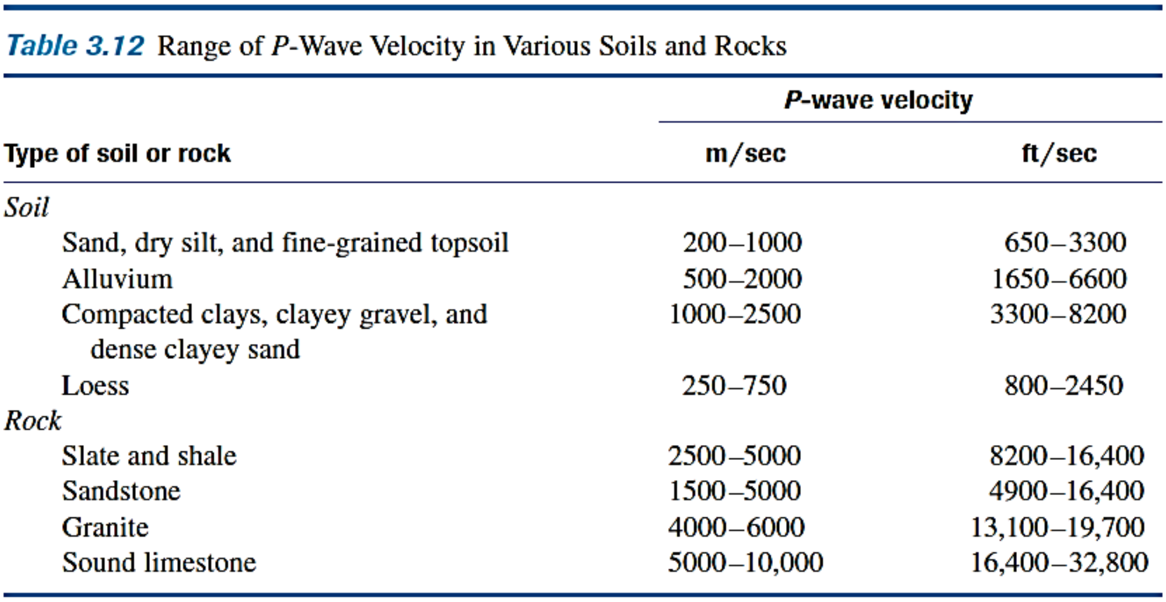


Table 3.12 Range of *P*-Wave Velocity in Various Soils and Rocks

Type of soil or rock	*P*-wave velocity m/sec	*P*-wave velocity ft/sec
Soil		
Sand, dry silt, and fine-grained topsoil	200–1000	650–3300
Alluvium	500–2000	1650–6600
Compacted clays, clayey gravel, and dense clayey sand	1000–2500	3300–8200
Loess	250–750	800–2450
Rock		
Slate and shale	2500–5000	8200–16,400
Sandstone	1500–5000	4900–16,400
Granite	4000–6000	13,100–19,700
Sound limestone	5000–10,000	16,400–32,800

Seismic Refraction Problems and Limitations: Most of the problems that arise in the use of seismic refraction are due to field conditions. Seismic refraction theory assumes the following conditions exist:

(1) The soil and rock are to be considered homogeneous, isotropic and elastic material.
(2) No decrease in velocity with depth occurs; that is v1 < v2 < v3. …
(3) Contrast in elastic properties of adjacent layers exists.

- Soils, however, are neither homogeneous nor isotropic. Anomalies or discontinuities such as cavities, faults, boulders, and sinkholes can introduce errors if careful attention is not given to the interpretation of the seismic data.
- Most soil and rock deposits increase in density with depth which is in favor of the second assumption. If not, the velocity of the shock waves will not increase with depth and errors will be introduced. When velocities of adjacent strata are within about 60–90 m/s of each other, determination of depth to the interface is virtually impossible from seismic data.
- Layers of clay or shale (of low velocity) underlying limestone (of high velocity) will not be recognisable on a time distance plot. The thickness of the harder material will appear to include the thickness of the softer layer. This condition, known as the “hidden layer” problem, can be corrected to some extent. If a hidden layer problem is suspected, the maximum errors in depth determination can be detected using nomographs.
- Complications also arise if the elastic properties of the adjacent strata do not contrast enough to define the interface. A layer of hard clay lying on soft shale or sandstone is an example of this problem.

- When a soil is saturated below water table, the P-wave velocity may be deceptive. P-waves can travel with velocity of about 1500 m/s through water. For dry loose soil the velocity may be well below 1500 m/s. if the presence of the groundwater has not been detected, the P-wave velocity may be erroneously interpreted to indicate a stronger material (e.g. sandstone) than is actually present in the site.

In general, geophysical interpretation should always be verified by the results obtained from borings.

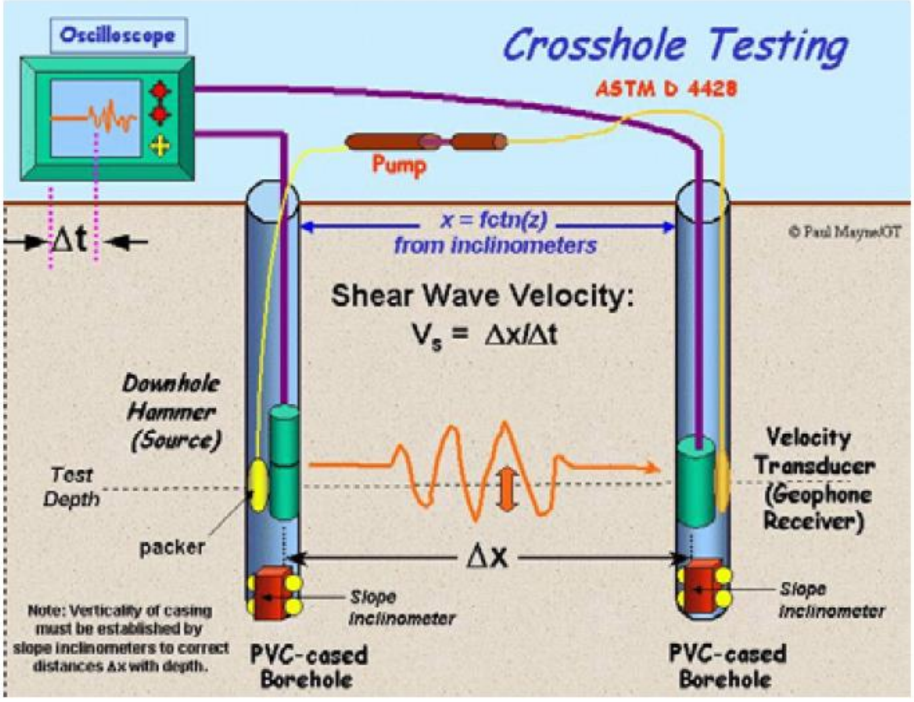
Cross hole Tests (CHT)

Cross hole tests are used for determining profiles of v_p and v_s with depth.

- Designated in ASTM D-4428
- CHT involves the use of down hole hammer and one or more down hole vertical geophones in an horizontal array of two or three boreholes spaced about 3 to 6m a part to determine the travel times of different strata.
- Can be conducted to a depth of 300m or more.
- Since the P-wave arrive first, its trace is already recorded on the oscilloscope. Therefore the S-wave is often masked because it comes later.
- The principle of this technique is illustrated in Figure, which shows two holes drilled into the ground a distance L apart. A vertical impulse is created at the bottom of one borehole by means of an impulse rod. The shear waves thus generated are recorded by a vertically sensitive transducer. The velocity of shear waves can be calculated as

$$v_s = \frac{L}{t}$$

where t = travel time of the waves.



The shear modulus Gs of the soil at the depth at which the test is taken can be determined from the relation

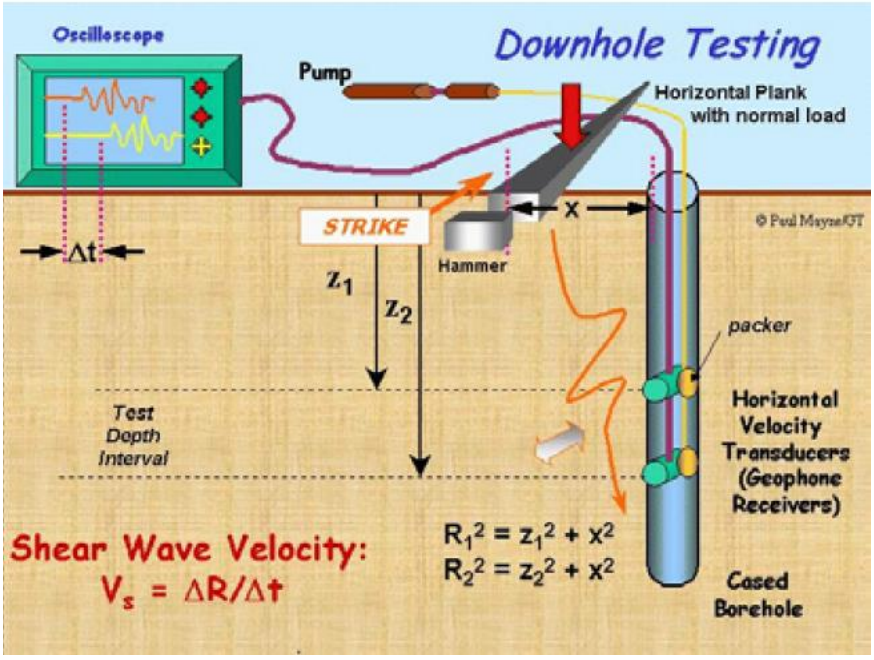
$$G_s = \frac{v_s^2 \ \gamma}{g}$$

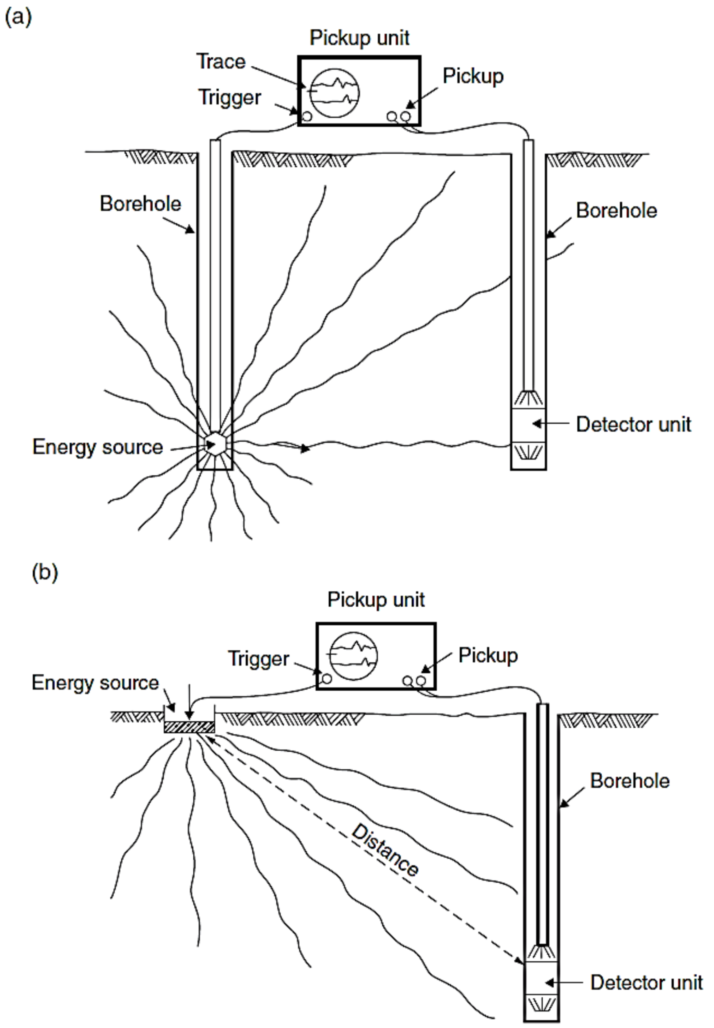
where
v_s = velocity of shear waves
γ =unit weight of soil
g = acceleration due to gravity
The shear modulus is useful in the design of foundations to support vibrating machinery and the like.

Down Hole Tests (DHT)

DHT can be performed using only one cased borehole

- S-waves are propagate down to the geophone from a stationary surface point. No inclinometer is needed.
- In DHT, a horizontal plank at the surface is statically loaded by a vehicle wheel (to increase normal stress)
- Struck lengthwise to provide an excellent shear wave source.
- A recent version of the DHT is the seismic cone penetration test (SCPT) with an accelerometer located within the penetrometer.
- The DHT provides direct reliable measurement of shear wave that are comparable to CHT results.





Two seismic methods for obtaining dynamic shear modulus. (a) Cross-hole method, (b) Down-hole method (from Bowles, 2001).

S-wave velocities range in common geotechnical materials at shallow depths.

Type of material	S-wave velocity (m/s)
Hard rocks (e.g. metamorphic)	1400+
Firm to hard rocks (e.g. igneous, conglomerates, competent sedimentary)	700–1400
Gravelly soils and soft rocks (e.g. sandstone, shale, soils with > 20% gravel)	375–700
Stiff clays and sandy soils	200–375
Soft soils (e.g. loose submerged fills and soft clays)	100–200
Very soft soils (e.g. marshland, reclaimed soil)	50–100

Electrical Resistivity Survey, ER

The methods depend on differences in the electrical resistance of different types of soil and rock. Resistivity of a material depends upon type of material, its water content and the concentration of dissolved salts in the pore water. The mineral particles of a soil are poor conductors of electric current; they are of high resistivity. Resistivity of a soil decreases (conductivity increases) as both the water content and pore water salts concentration increase. Approximate ranges of resistivity value for different types of soil and rock are given in the following table.

Material	Resistivity (ohm.m)
Sand	500–1500
Clays, saturated silt	0–100
Clayey sand	200–500
Gravel	1500–40 000
Weathered rock	1500–2500
Sound rock	> 1500

Resistivity of any conducting material having a length L and cross section area A is given by the equation:

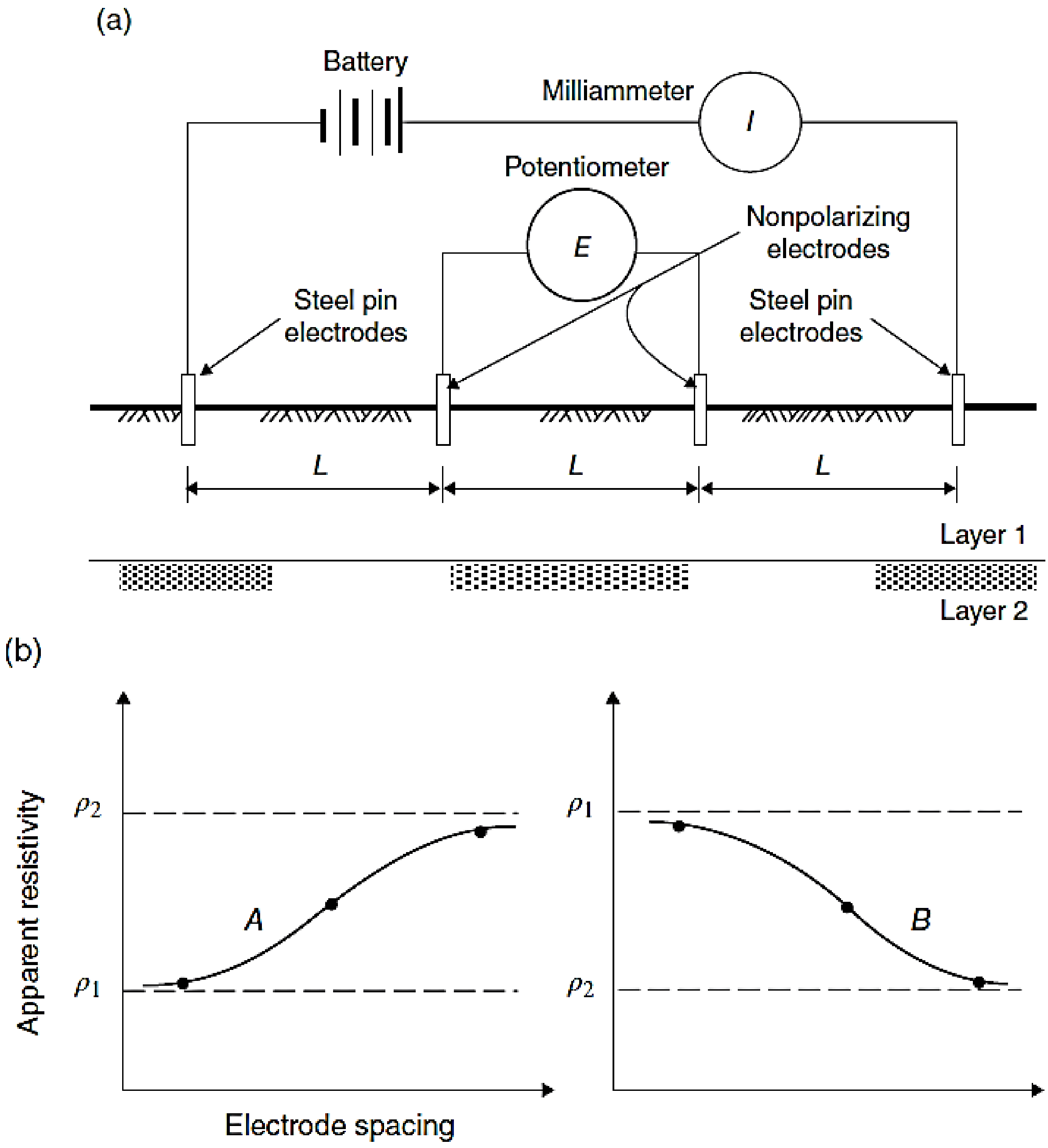
$$\rho = \frac{RA}{l}$$

where ρ = electrical resistivity (ohm.m)

$$R = \text{electrical resistance (ohm)} = \frac{\text{voltage drop } E}{\text{current } I} \text{ (Ohm's law)}$$

The in situ common electrical sounding procedure involves driving four electrodes, which are usually in theform of metal spikes, into the ground at equal distances L apart in a straight line. The two outer electrodes are known as current electrodes, and the inner electrodes are called potential electrodes. The current I, usually 50–100 mA, from a battery, flows through the soil between the two current electrodes producing an electrical field within the soil. The potential (voltage) drop E is then measured between the two potential lectrodes.
The mean (apparent) resistivity ρ is given by the equation:

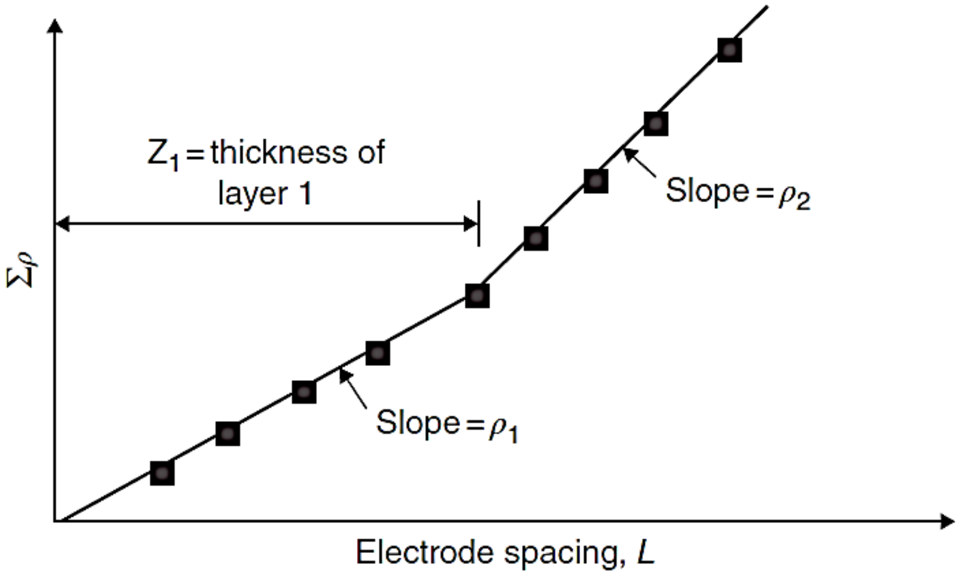
$$\rho = \frac{2\pi L E}{I}$$



- The equation gives the mean resistivity up to a depth equals the distance L below the ground surface, as the depth of current penetration below the ground surface is approximately equal to the spacing L of the two potential electrodes.
- Aseries of readings are taken, the (equal) spacing of the electrodes being increased for each successive reading; however the central position of the four electrodes remains unchanged. As L is increased, the resistivity ρ is influenced by a greater depth of soil.The

distance L is thus gradually increases to a distance equal to the required depth of exploration.

- The maximumdepth is usually about 30mor so. If ρ decreaseswith increasing L a stratumof lower resistivity, such as a saturated clay layer, is beginning to influence the readings. If ρ increases with increasing L it can be concluded that an underlying stratum of higher resistivity, such as a gravel layer, is beginning to influence the readings.
- The mean resistivity ρ is plotted against the electrode spacing L, preferably on log-log paper. Characteristic curves for a two-layer structure are illustrated in the figure. For curve A the resistivity of layer 1 is lower than that of layer 2; for curve B the resistivity of layer 1 is higher than that of layer 2. The curves become asymptotic to lines representing the true resistivity ρ1 and ρ2 of the respective layers.
- Approximate layer thickness can be obtained by comparing the observed curve of ρ versus L with a set of standard curves, or, by using other methods of interpretation, such as the method illustrated by the graph of the following figure, which relates the sum of the apparent resistivity Σρ to the electrode spacing. In this figure, the slopes ρ1 and ρ2 are actual resistivity of layers 1 and 2, respectively.



An approximate method for determining resistivity and thickness of subsurface layers.

Resistivity Problems and Limitations: The theoretical basis for electrical resistivity assumes:
(1) The soil or rock is homogeneous and isotropic.
(2) Uniform resistivity exists.
(3) The soil layers are parallel to each other and to ground surface.
Unfortunately, the assumed soil conditions seldom exist in the field because soil and rock are not homogeneousand isotropic. Therefore the user must be aware of the effects on data caused by anomalies, such as faults, folded layers, caves, sinkholes or intermixing of

soil and rock in the layers. Also, buried pipelines, underground cables, tunnels or any buried metallic materials will cause anomalous readings.

Nonparallel layers cause bending or warping of the current flow lines causing erroneous resistivity readings. If the ground surface and the interfaces are not parallel the exact depth below centre of the fixed location (centre of the spread) may not be found due to varying layer thickness.

Materials differ in their electrical resistivity. The resistivity of materials does not change due to texture only, but also because of the changes in the moisture and electrolytic content. As a result, considerable overlapping of the resistivity of various materials will exist. Overlapping makes interpretation of resistivity data very difficult in some cases.

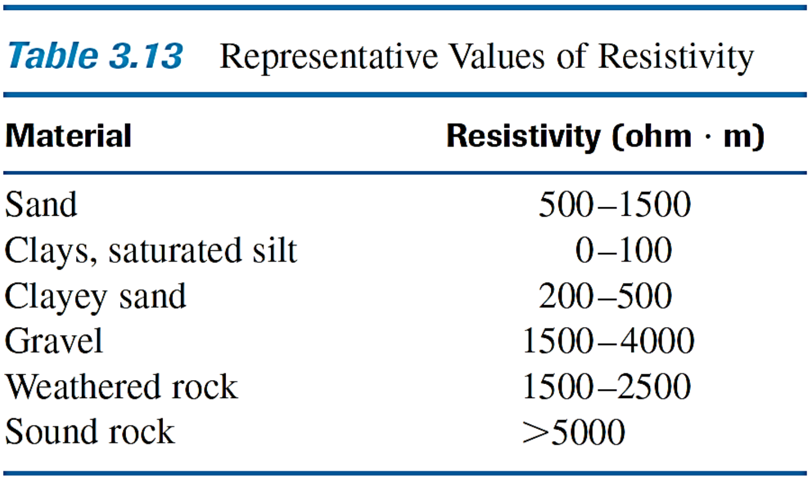


Table 3.13 Representative Values of Resistivity

Material	Resistivity (ohm · m)
Sand	500–1500
Clays, saturated silt	0–100
Clayey sand	200–500
Gravel	1500–4000
Weathered rock	1500–2500
Sound rock	>5000