FOUNDATION ENGINEERING

Soil Exploration: Boring

Introduction

- The field and laboratory investigations required to obtain the necessary data for the soils for proper design and successful construction of any structure at the site are collectively called *soil exploration* .
- The choice of the foundation and its depth, the bearing capacity, settlement analysis depend very much upon the various engineering properties of the foundation soils.

The primary objectives of soil exploration are

- Determination of the nature of the deposits of soil, depth and thickness of various soil strata.
- Location of Ground water table and obtaining soil and rock samples from the various strata.
- The determination of the engineering properties of the soil and rock strata that affect the performance of the structure.
- Determination of the *in-situ* properties by performing field tests.

Soil data required

- **Soil profile**

  – layer thickness and soil identification

- **Index properties**

  - water content, Atterberg limits, etc.

- **Strength & compressibility characteristics**

  – c', ϕ', C_c, OCR, …

- **Others (e.g., water table depth)**

Direct Methods – Test Pits

- Test pits or trenches are open type or accessible exploratory methods.
- Soils can be inspected in their natural condition.
- The necessary soils samples may be obtained by sampling techniques and used for finding strength and other engineering properties by appropriate laboratory tests.

Direct Methods – Test Pits

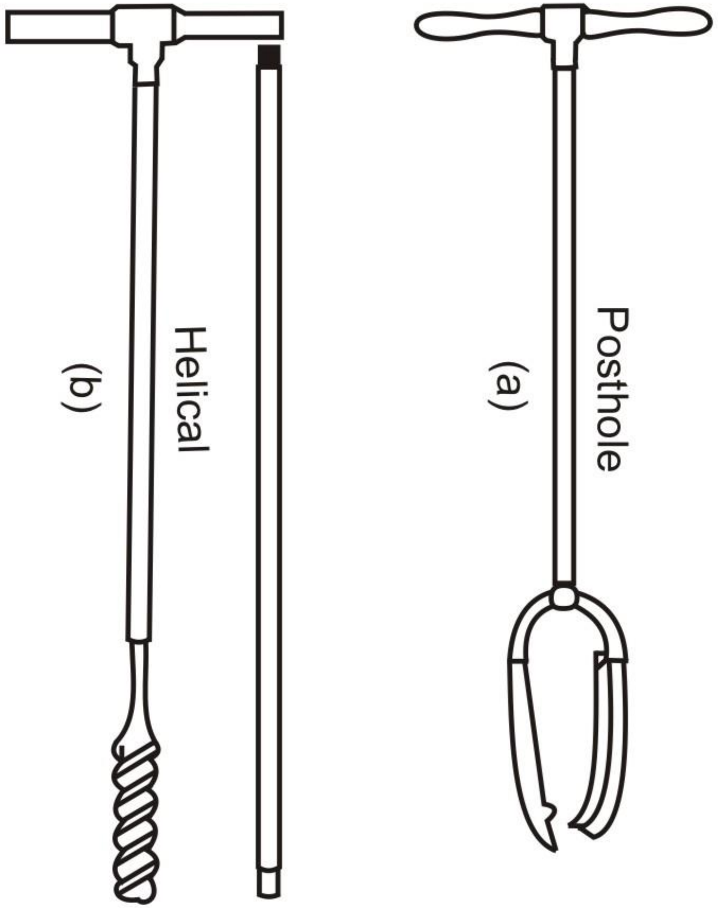
- Test pits are considered suitable only for small depths – up to 3m; the cost of these increases rapidly with depth.
- For greater depths, lateral supports or bracing of the excavations will be necessary .
- Test pits are usually made only for supplementing other methods or for minor structures.

Semi Direct Methods - Boring

- Boring: Making or drilling bore holes into the ground with a view to obtaining soil or rock samples from specified or known depths is called '*boring*'
- The common methods of advancing bore holes are:
  - Auger boring
  - Wash boring
  - Rotary drilling
  - Percussion drilling

Auger Boring

- ‘Soil auger’ is a device that is useful for advancing a bore hole into the ground.
- Augers may be hand-operated or power-driven; the former are used for relatively small depths (less than 3 to 5 m), while the latter are used for greater depths (upto 60 to 70 m in case of continuous-flight augers).
- Augur boring is convenient in case of partially saturated sands, silts and medium to stiff cohesive soils.



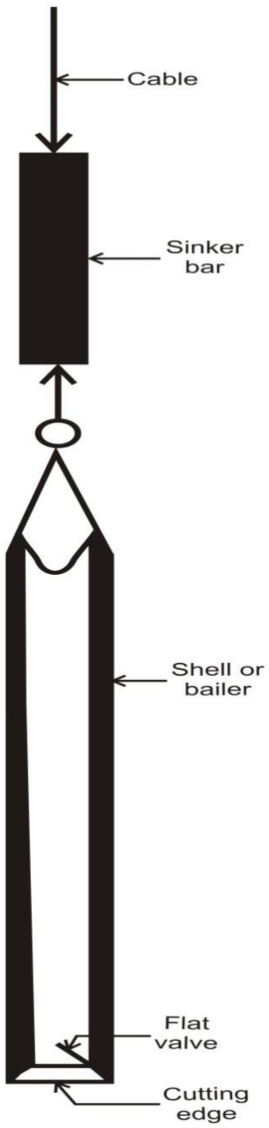
Auger boring

Process

The soil auger is advanced by rotating it while pressing it into the soil.

As soon as the auger gets filled with soil, it is taken out and the soil sample collected.

The soil samples obtained from this type of borings are highly disturbed

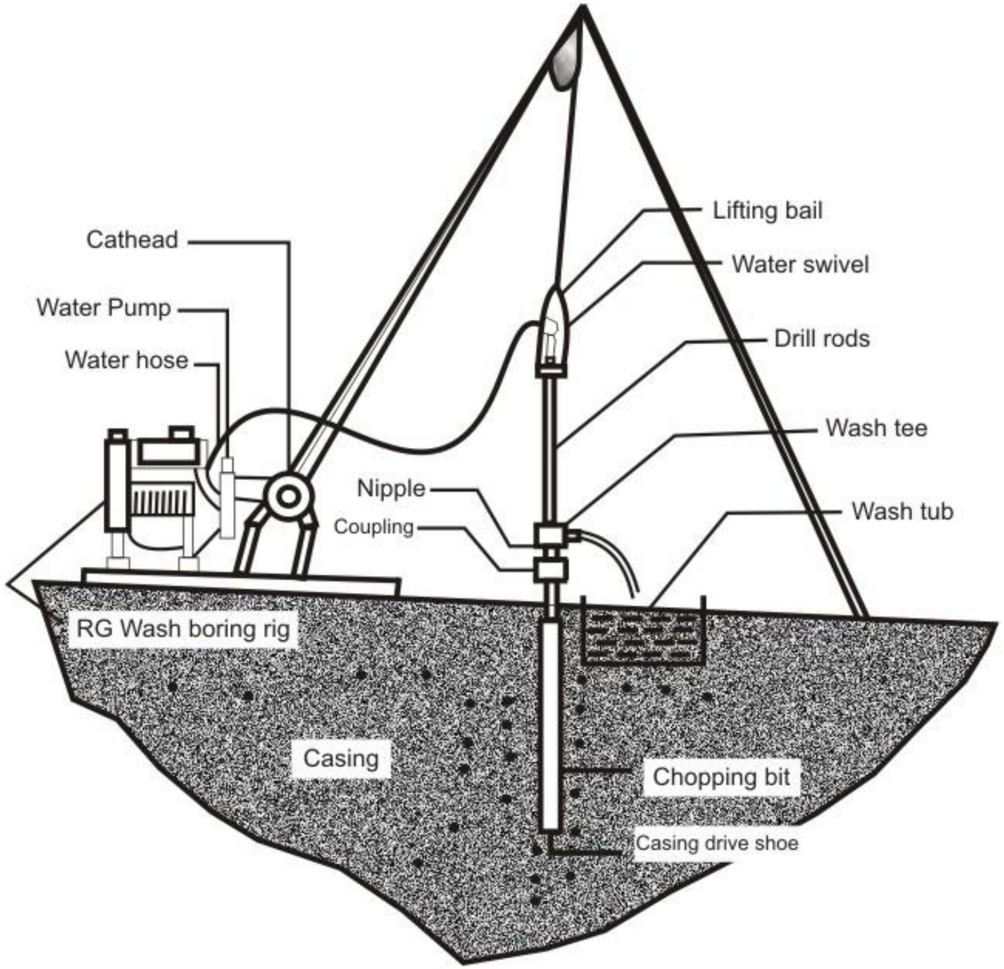


Shell and Auger

- Used widely in India
- The shell, (called a sand bailer) is a heavy duty pipe with a cutting edge.
- The shell is raised and let fall in a hole. The soil is cut, enters the tube which is emptied when full.
- Shell is used when auger boring becomes difficult.

Wash Boring

- Wash boring is commonly used for exploration below ground water table for which the auger method is unsuitable.
- This method may be used in all kinds of soils except those mixed with gravel and boulders.
- A casing pipe is pushed in and driven with a drop weight.



Process

A casing pipe is pushed in and driven with a drop weight.

hollow drill bit is screwed to a hollow drill rod connected to a rope passing over a pulley and supported by a tripod.

Water jet under pressure is forced through the rod and the bit into the hole which loosens the soil.

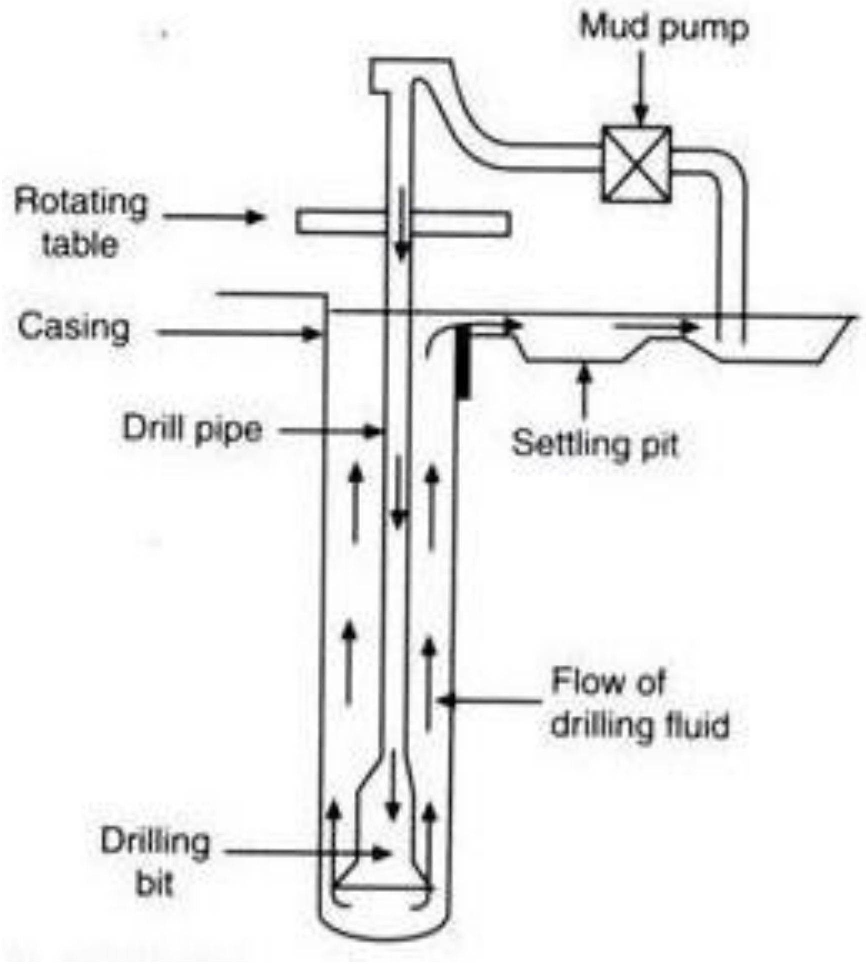
The soil-water suspension forced upward is led to a settling tank where the soil particles settle while the water overflows into a sump.

Wash Boring

- The soil particles collected represent a very disturbed sample and is not very useful for the evaluation of the engineering properties.
- Wash borings are primarily used for advancing bore holes; whenever a soil sample is required, the chopping bit is to be replaced by a sampler.
- The change of the rate of progress and change of colour of wash water indicate changes in soil strata.

Rotary Drilling

- Can be used in sand, clay and rocks (unless badly fissured)
- This is a very fast method.
- Even rock cores may be obtained by using suitable diamond drill bits.



Process

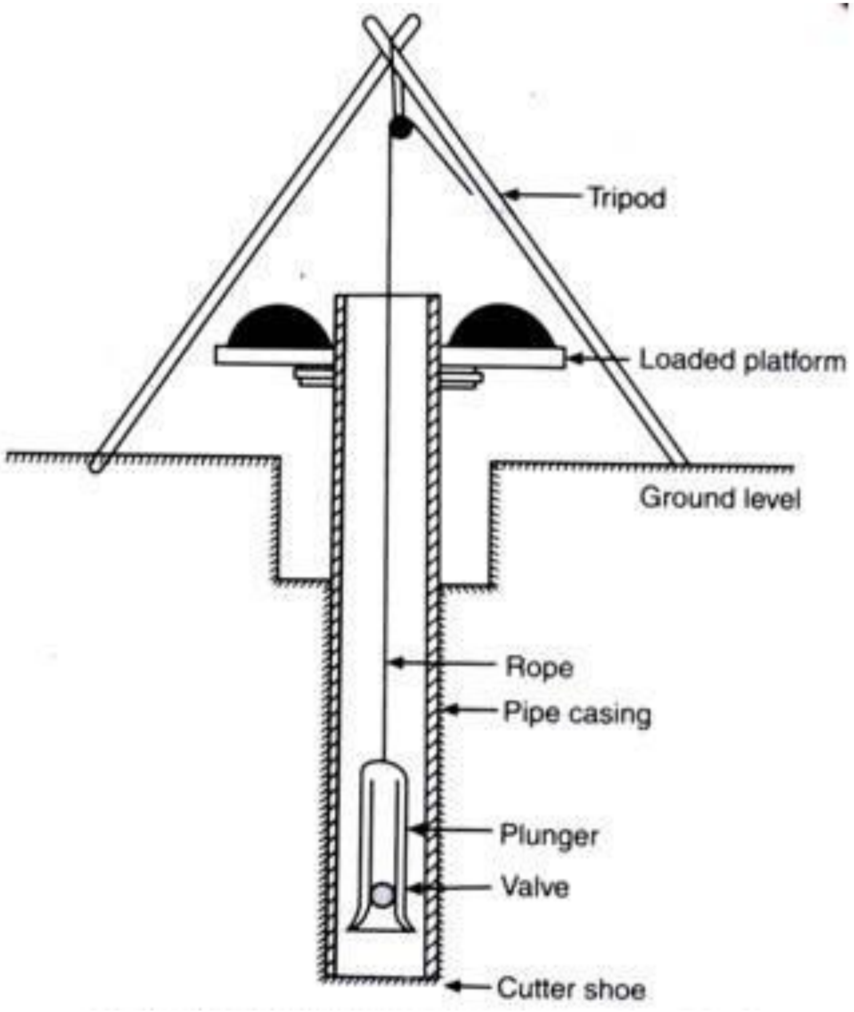
A drill bit, fixed to the lower end of a drill rod, is rotated by power while being kept in firm contact with the hole.

Drilling fluid or bentonite slurry is forced under pressure through the drill rod and it comes up bringing the cuttings to the surface.

When soil samples are required, the drilling rod raised and drilling bit is replaced by a sampler.

Percussion Drilling

- The method cannot be used in loose sand and is slow in plastic clay.
- The formation gets badly disturbed by impact.



Process

A heavy drill bit is suspended from a drill rod or a cable and is driven by repeated blows.

Water is added to facilitate the breaking of stiff soil or rock.

The slurry of the pulverised material is bailed out at intervals.

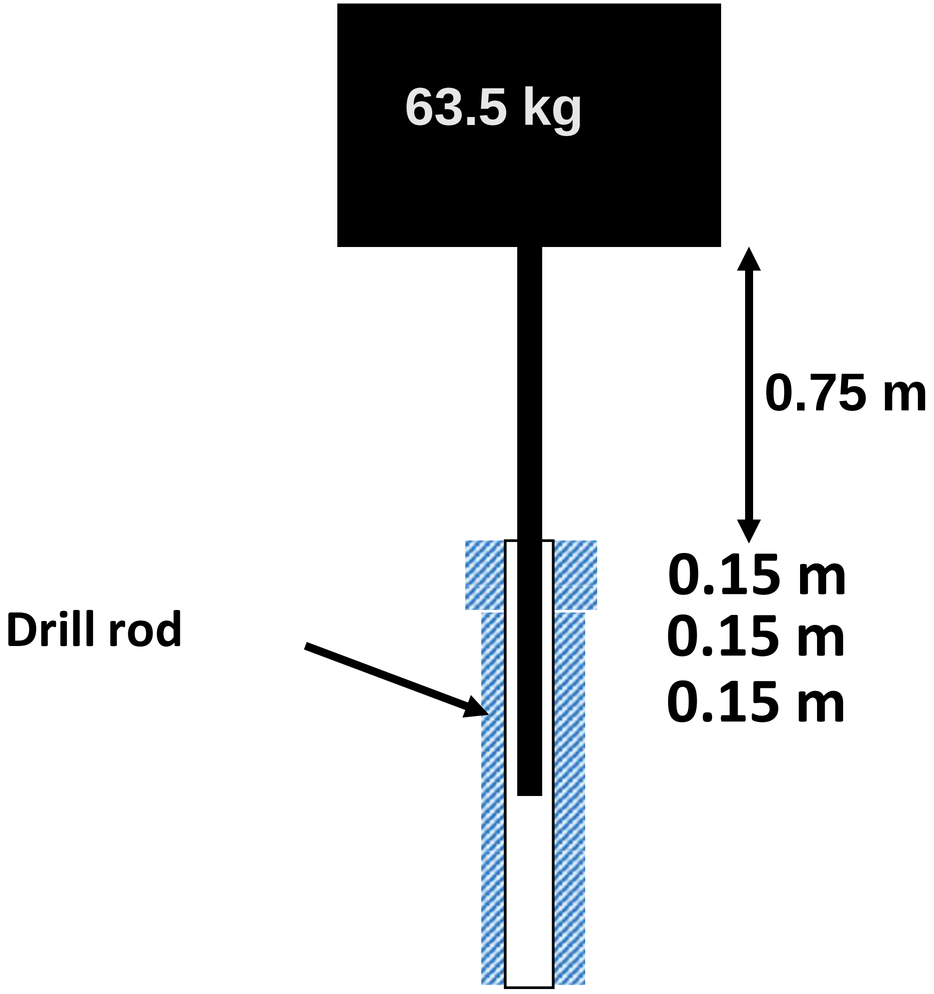
Standard
Penetration Test

Indirect Method

Standard Penetration Test (SPT) IS: 2131-1981

- The Standard Penetration Test (SPT) is widely used to determine the parameters of the soil *in-situ*. The test consists of driving a **split-spoon sampler** into the soil through a bore hole at the desired depth.
- The split-spoon sampler is driven into the soil a distance of **450 mm** at the bottom of the boring
- A hammer of **63.5 kg** weight with a free fall of **750 mm** is used to drive the sampler.

- The number of blows for a penetration of **last 300 mm** is designated as the “Standard Penetration Value” or “Number” *N*.
- The test is usually performed in three stages. The blow count is found for every 150 mm penetration .
- The blows for the first 150 mm are ignored as those required for the seating drive.



Number of blows for the first 150 mm penetration is disregarded due to the disturbance likely to exist at the bottom of the drill hole

The test can be conducted at every 1m vertical intervals (Not more than 1.5 m)

Number of blows = N_1

Number of blows = N_2

Number of blows = N_3

Standard penetration resistance (SPT N) = $N_2 + N_3$

The refusal of test when

- 50 blows are required for any 150 mm increment.
- 100 blows are obtained for required 300 mm penetration.
- 10 successive blows produce no advance.

Standard Penetration Test (SPT):IS: 2131-1981

Two corrections due to:

(a) Overburden pressure (granular soil)

(b) Dilatancy (for saturated fine sands and silts)

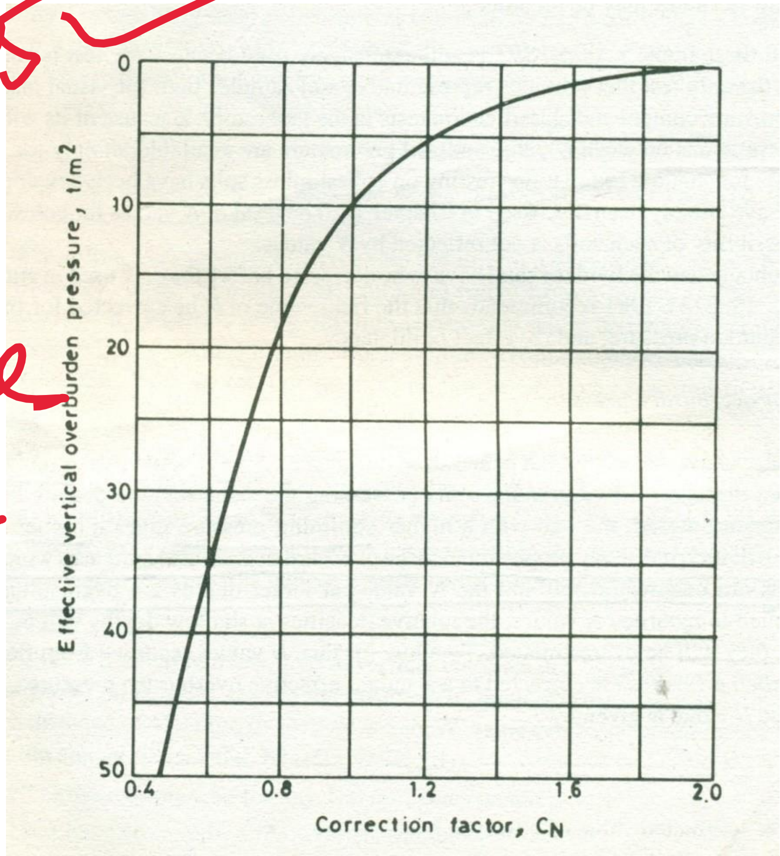
The corrected N value is given by

$$N' = C_N\, N$$

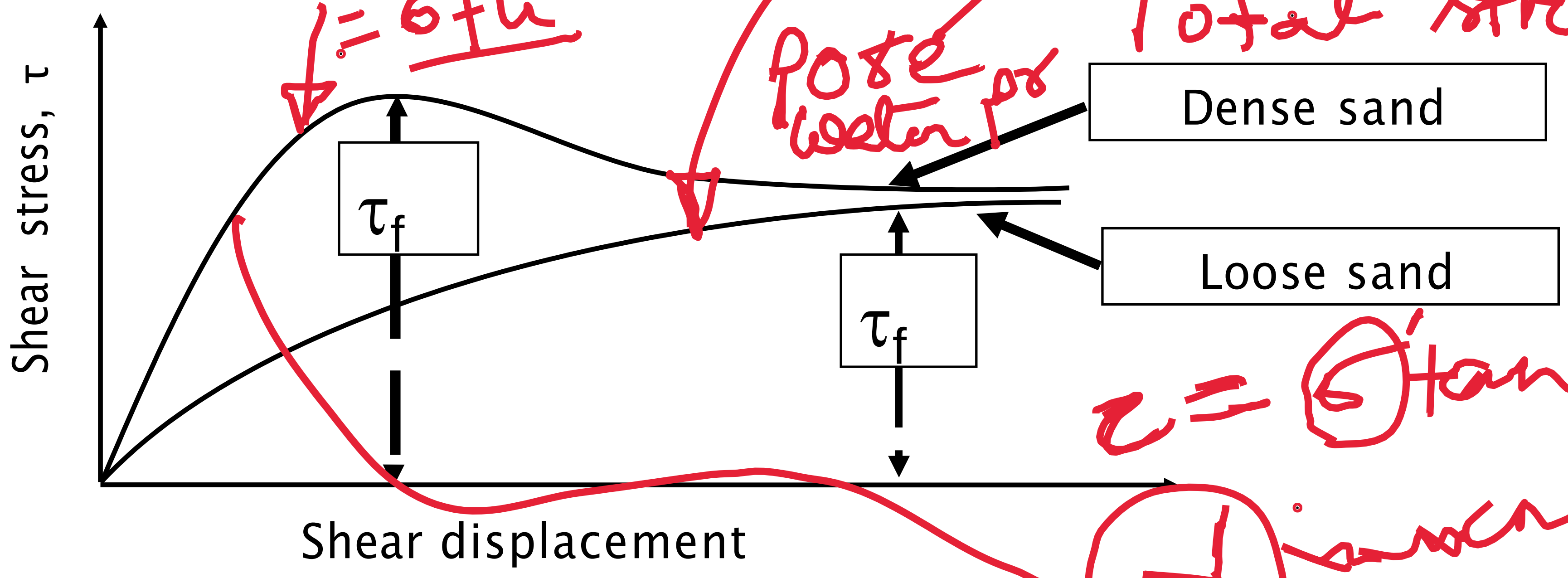
where N' = corrected value of observed N

C_N = correction factor for overburden pressure

$$N'' = 15 + 0.5(N' - 15) \text{ if } N' > 15$$



Stress-strain relationship



BOREHOLE LOG

Location :

Project :

Boring method : Shell and auger

Diameter : 150 mm

BH No.1

Ground RL : 46.3 m

Date of start : 1.1.1998

Completed on : 4.1.1998

Description of start	R.L.	Legend	Depth	Samples	N	q_u kN/m^2	Remarks
Loose, light brown SAND (SP)				R	6		
	43.7		2.6				
Medium dense brown gravelly SAND (SW) ▽W.T.				R	18		
	42.5						Water level : 1.1.98 42.8 m; 2.1.98 42.5 m; 3.1.98 42.5 m
	41.9		4.4	R	20		
Firm to stiff, yellowish-brown, CLAY of high plasticity (CH)				U		160	
				U		180	
				U		200	
				U		210	
	34.0		12.3				
Very dense, red, silty SAND (SM)				R	50		
				R	62		
					50 for 150mm		Refusal
	30.0		16.3				Termination level of borehole 30.0 m

U: Undisturbed R : Representative sample

Indirect Method

Cone Penetration Test (CPT)

Dynamic cone penetration test (DCPT)

- similar to SPT; hammer driven
- using cone instead of split spoon

closed end; no samples

- gives blow counts @ 1.5 m depth intervals

Static cone penetration test (SCPT)

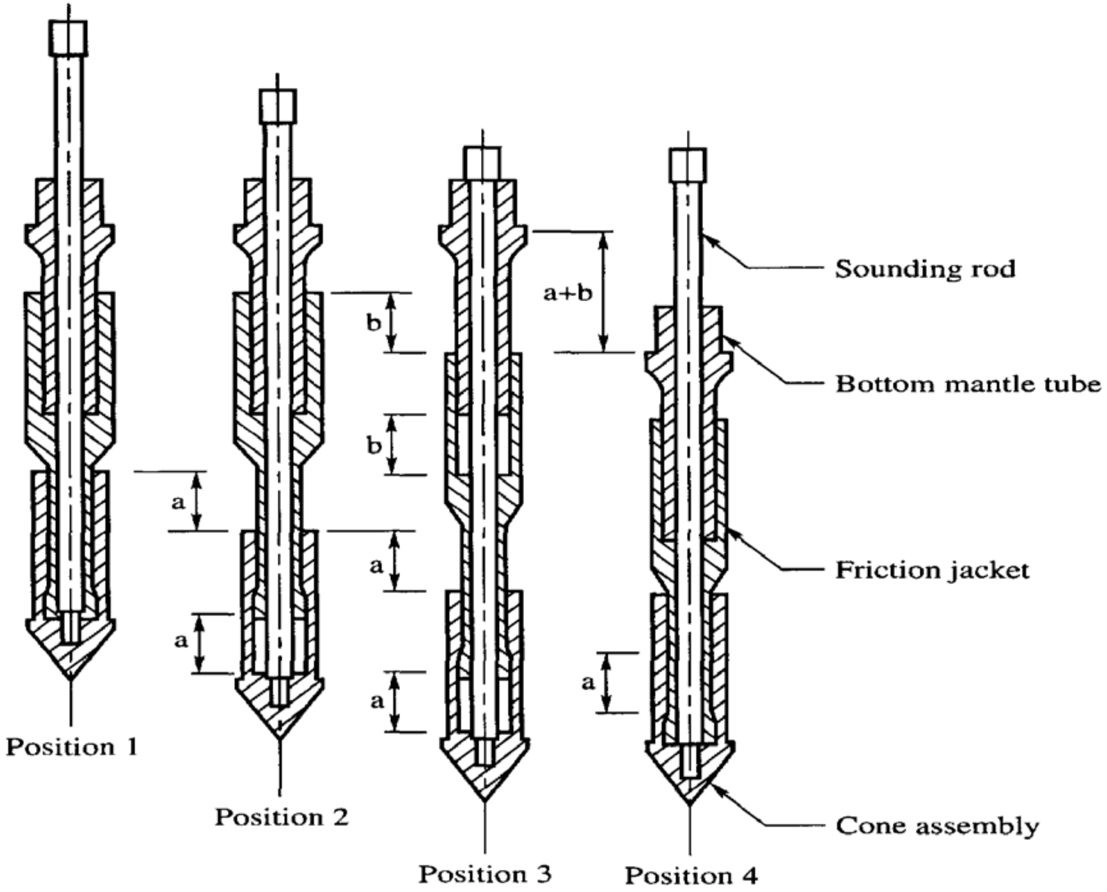
- pushed into the ground @ 1 cm/s
- gives continuous measurements

Static Cone Penetration Test

- The Static cone penetration test, which is also known as Dutch Cone test, has been standardized by “**IS: 4968 (Part -III)-1976** – Method for subsurface sounding for soils – Part III Static cone penetration test”.
- The equipment consists of **a steel cone, a friction jacket, sounding rod, mantle tube, a driving mechanism and measuring equipment**.
- The cone have an **apex angle of 60° ± 15′ and overall base diameter of 35.7 mm giving a cross-sectional area of 10 cm^2.**

- The friction sleeve should have an area of **150 cm^2** as per standard practice.
- The sounding rod is a steel rod of 15 mm diameter which can be extended with additional rods of 1 m each in length.
- The driving mechanism should have a capacity of **20 to 30 kN** for manually operated equipment and **100 kN** for the mechanically operated equipment.

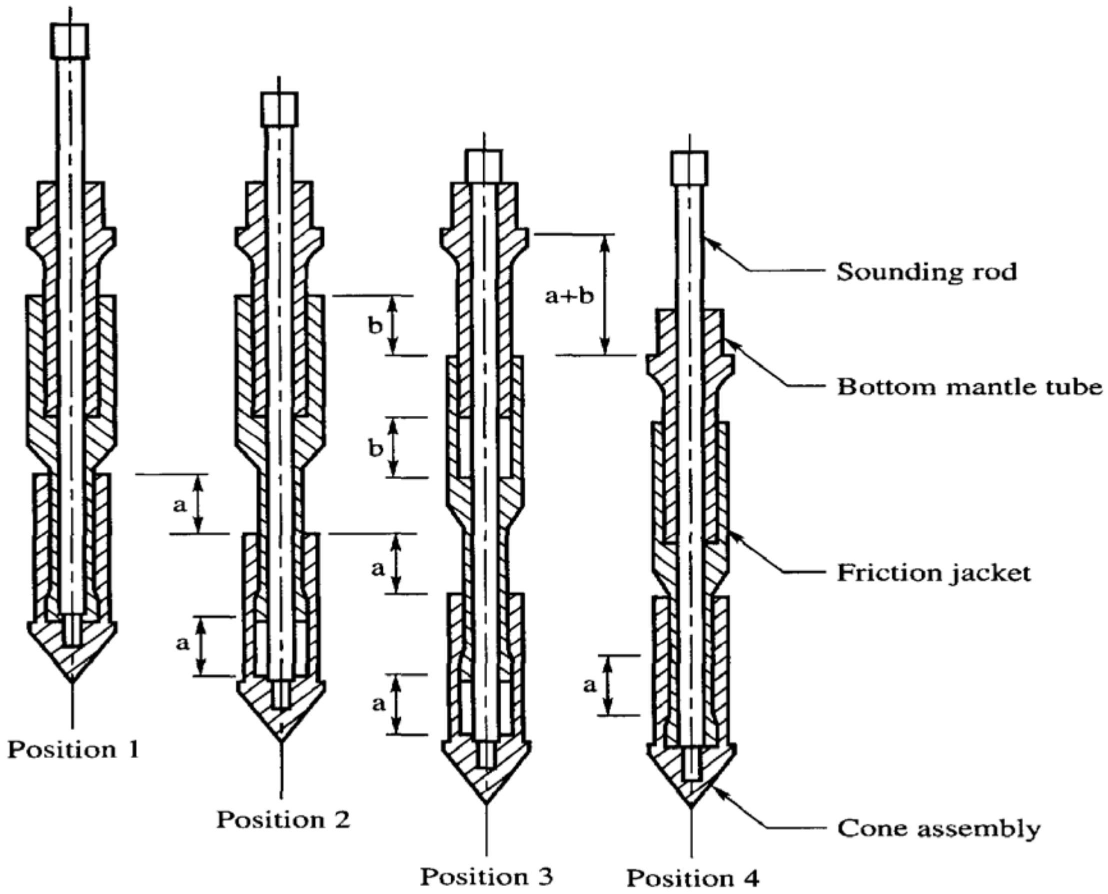
Operation of Penetrometer



The sequence of operation of the penetrometer as follows:

- **Position 1**: The cone and friction jacket assembly in a collapsed position.
- **Position 2**: The cone is pushed down by the inner sounding rods to a depth *a* until a collar engages the cone. The pressure gauge records the total force Q_c to the cone. Normally a = 40 mm.

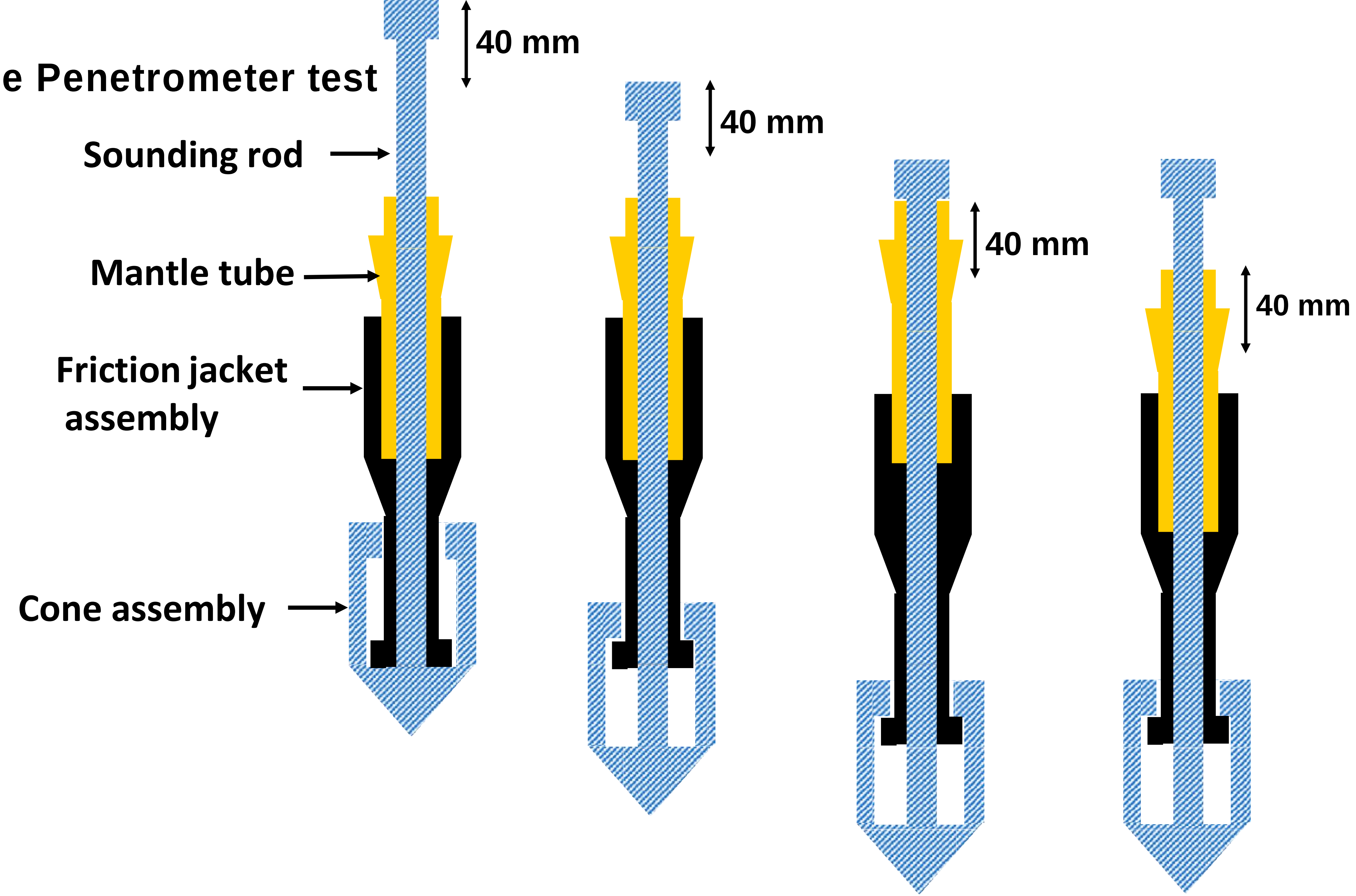
Operation of Penetrometer



- **Position 3**: The sounding rod is pushed further to a depth *b*. This pushes the friction jacket and the cone assembly together; the force is Q_t. Normally b = 40 mm.

- **Position 4**: The outside mantle tube is pushed down a distance $a + b$ which brings the cone assembly and the friction jacket to position 1. The total movement = $a + b$ = 80 mm.

Static Cone Penetrometer test



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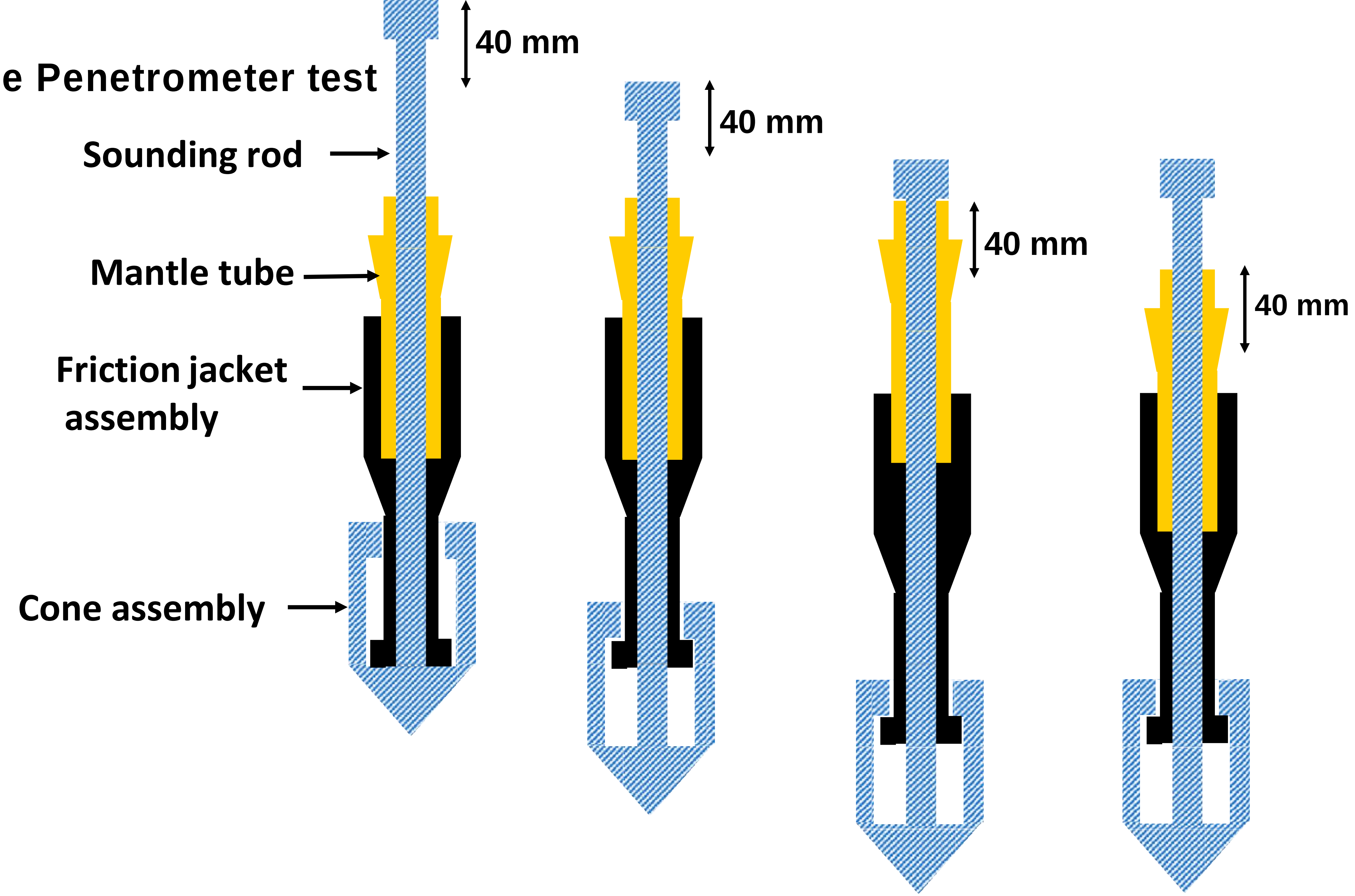
Static Cone Penetrometer test



SCPT Correlations

In Clays,

$$c_u = \frac{q_c - \sigma_v}{N_k}$$

c_u = Undrained shear strength of

σ_v = total vertical stress at the depth of penetration

q_c = The cone tip resistance

N_k = cone factor (15 – 20)

15 → Electric cone; 20 → mechanical cone

In Sand,

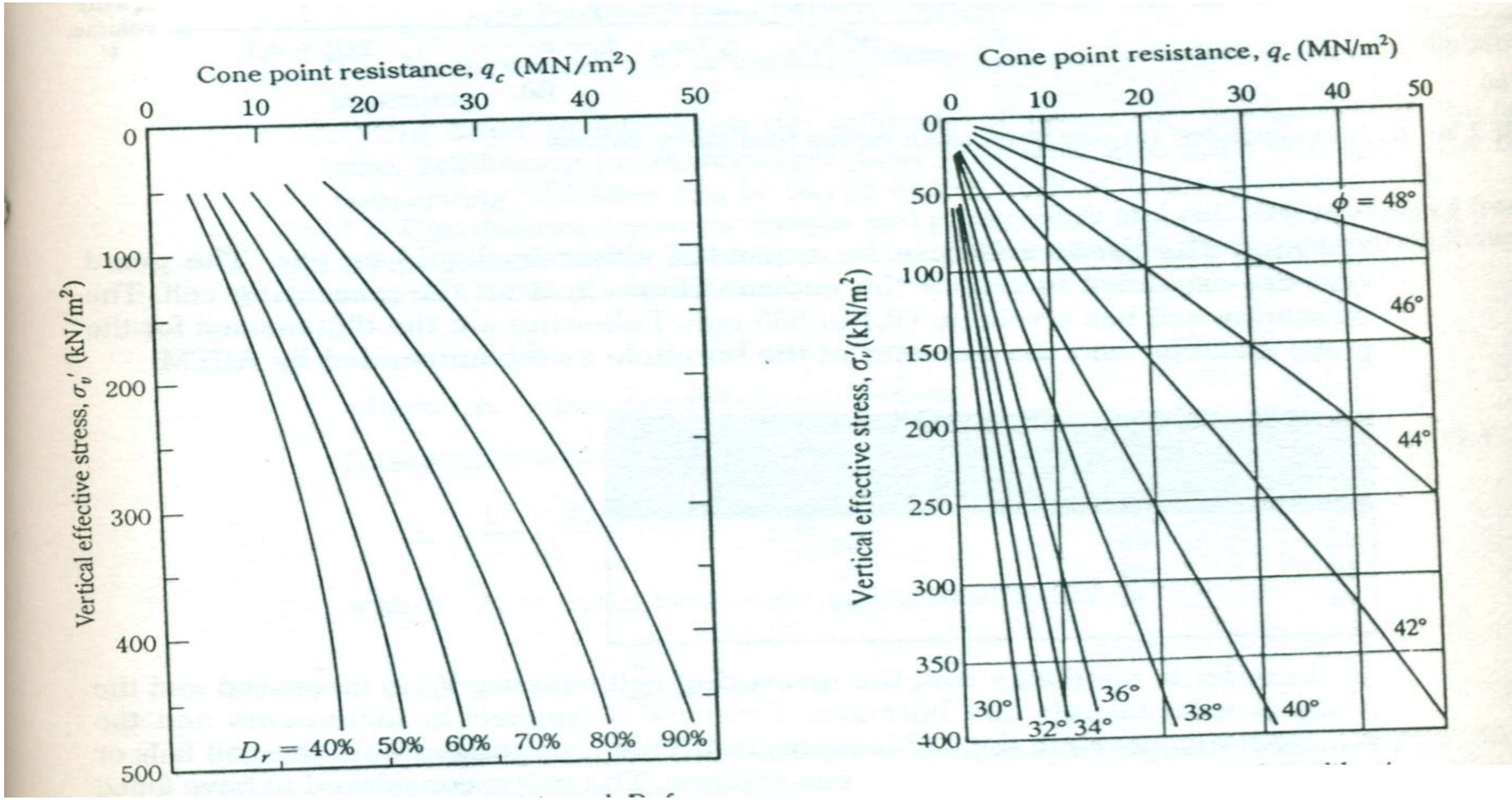
$$\phi = \tan^{-1}\left[0.1 + 0.38 \log\left(q_c/\sigma_v'\right)\right]$$ (Kulhawy and Mayne, 1990)

where

ϕ is the friction angle

q_c is the cone resistance

σ_v' (or p_0') is the vertical effective overburden pressure or stress

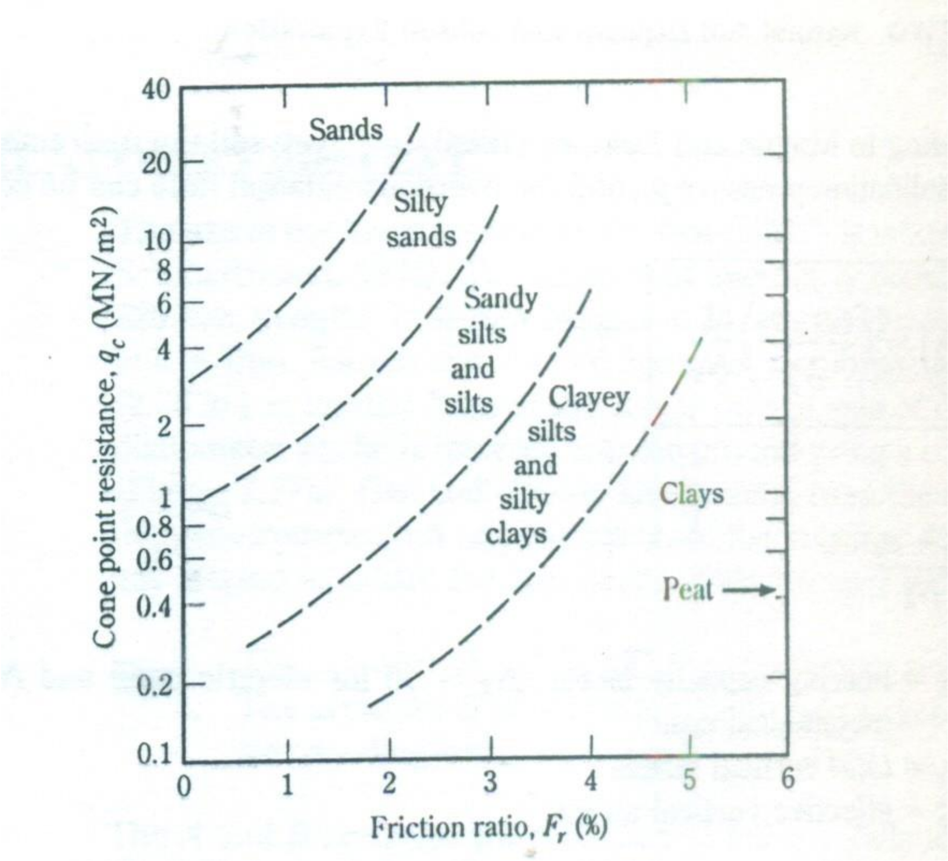


Normally consolidated quartz sand (after Robertson and Campanella, 1983)

$$Friction\ ratio, F_r = \frac{f_s}{q_c}$$

Cone resistance or cone tip resistance (q_c)

Sleeve friction (f_s)



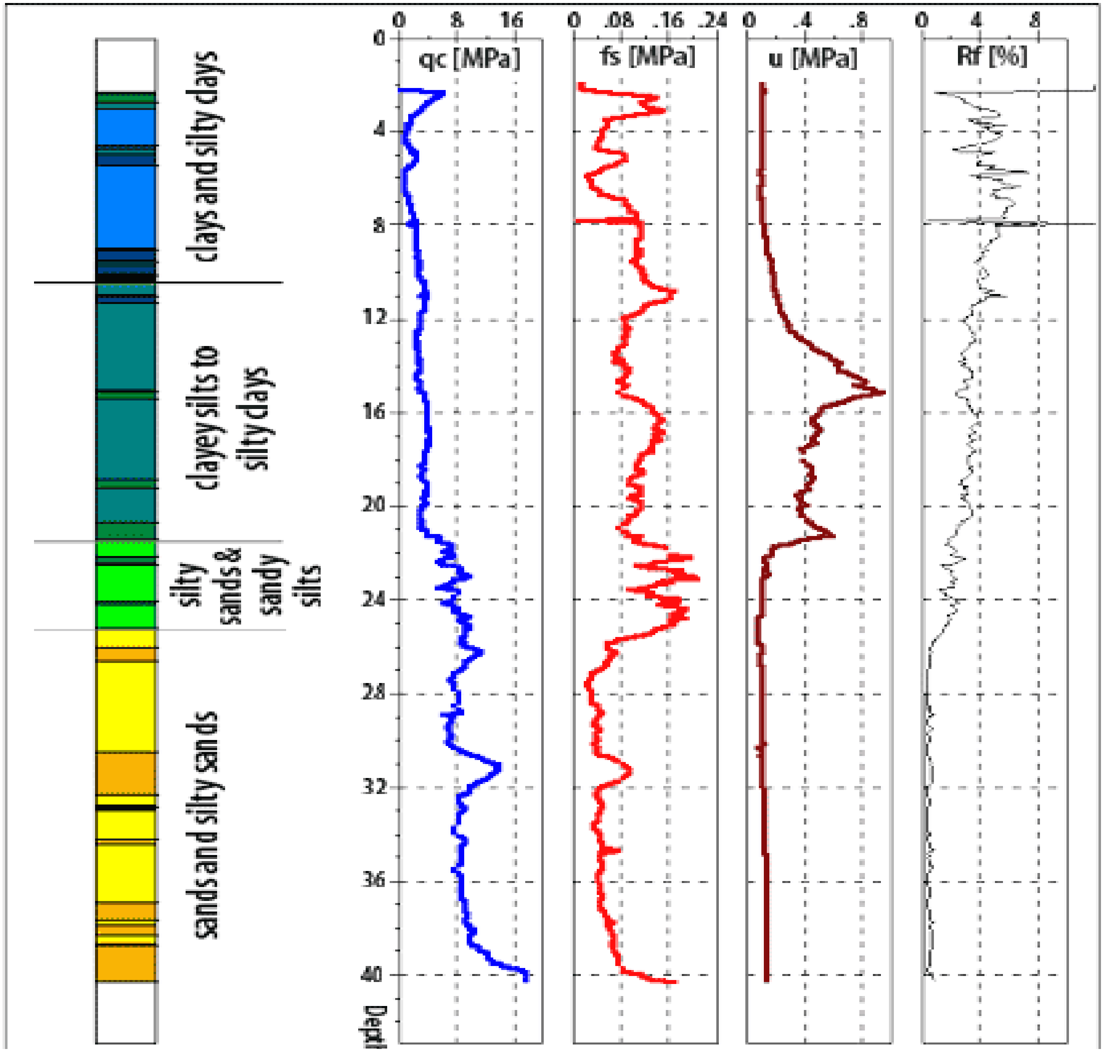
Piezocone

Pushed into the ground

Porous stone for pore pressure measurement

A modern static cone; measures pore water pressure also.

Piezocone with leads



clays and silty clays
clayey silts to silty clays
silty sands & sandy silts
sands and silty sands
qc [MPa]
fs [MPa]
u [MPa]
Rf [%]
Depth

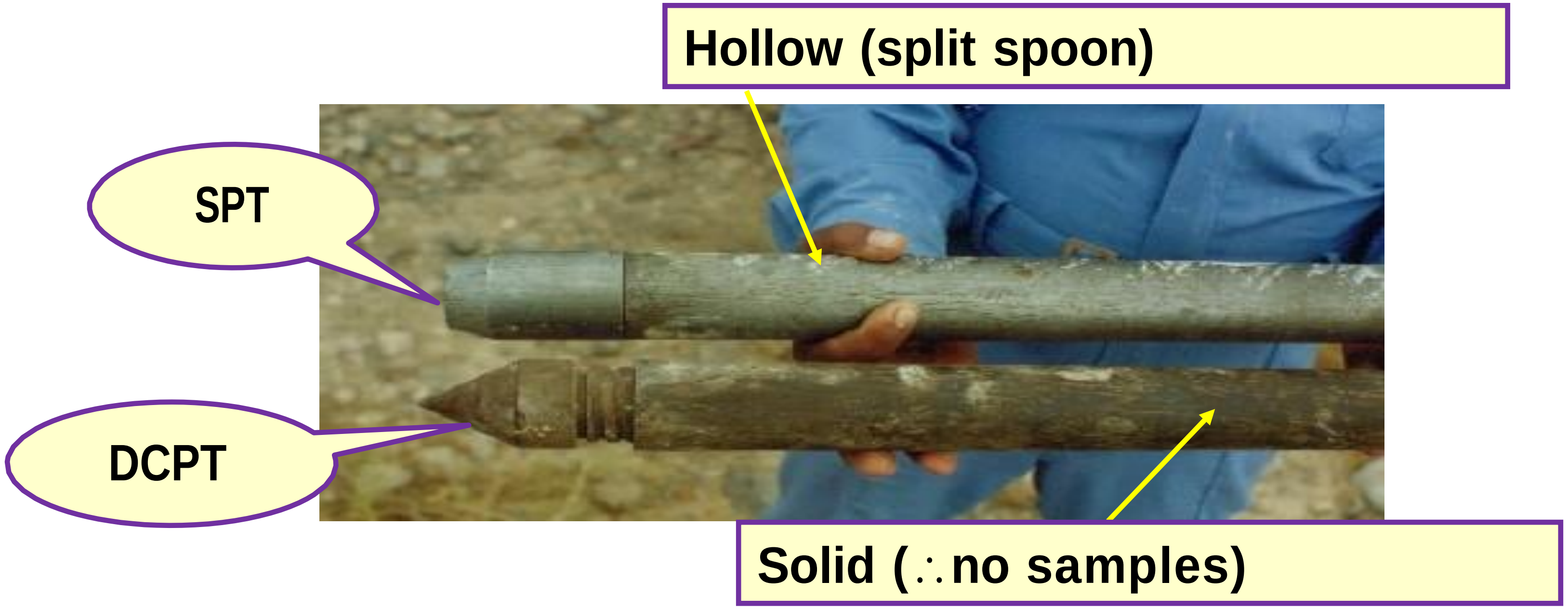
Dynamic Cone Penetration Test

- The dynamic cone penetration test is standardised by **“IS: 4968 (Part I) – 1976** – Method for Subsurface Sounding for Soils-Part I Dynamic method using 50 mm cone without bentonite slurry”.
- The equipment consists of **a cone, driving rods, driving head, hoisting equipment and a hammer.**
- The hammer used for driving the cone shall be of mild steel or cast-iron with a base of mild steel and the weight of the hammer shall be **640 N (65 kg).**

- The cone shall be driven into the soil by allowing the hammer to fall freely through **750 mm** each time.
- The number of blows for every **100 mm** penetration of the cone shall be recorded.
- The process shall be repeated till the cone is driven to the required depth.

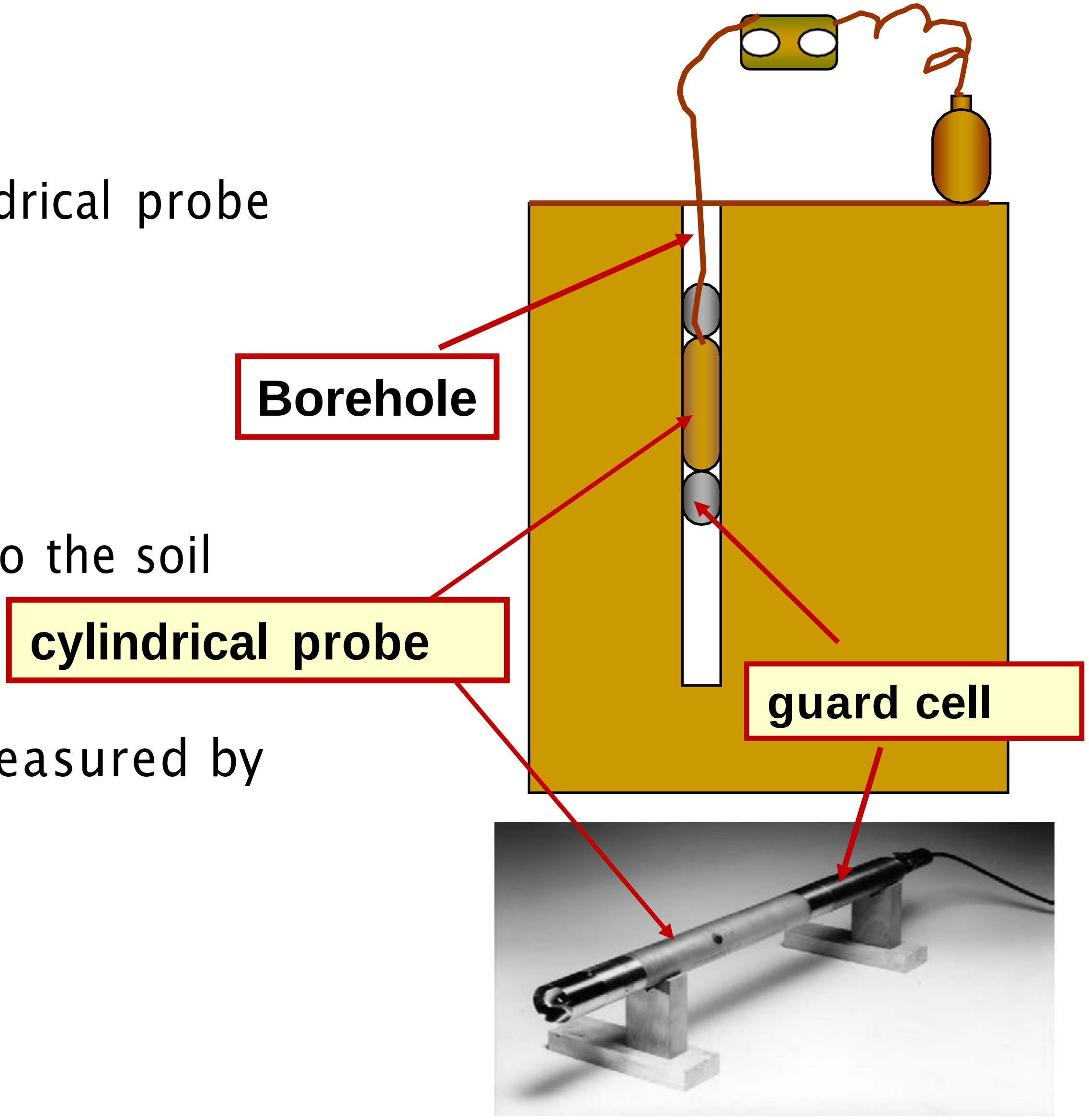
Dynamic Cone Penetration Test

- Better than SPT or SCPT in hard soils such as dense gravels
- As crude as SPT; relies on correlations based on blow counts



Pressuremeter Test

- The pressure meter consists of an inflatable cylindrical probe which is connected to a water reservoir.
- Expand cylindrical probe inside a bore hole.
- The probe presses against the wall of bore hole. So the soil begins to deform
- The volumetric deformation of the borehole is measured by noting the fall in water level in the water reservoir



IS: 1892-1979 describes the use of pressure meter

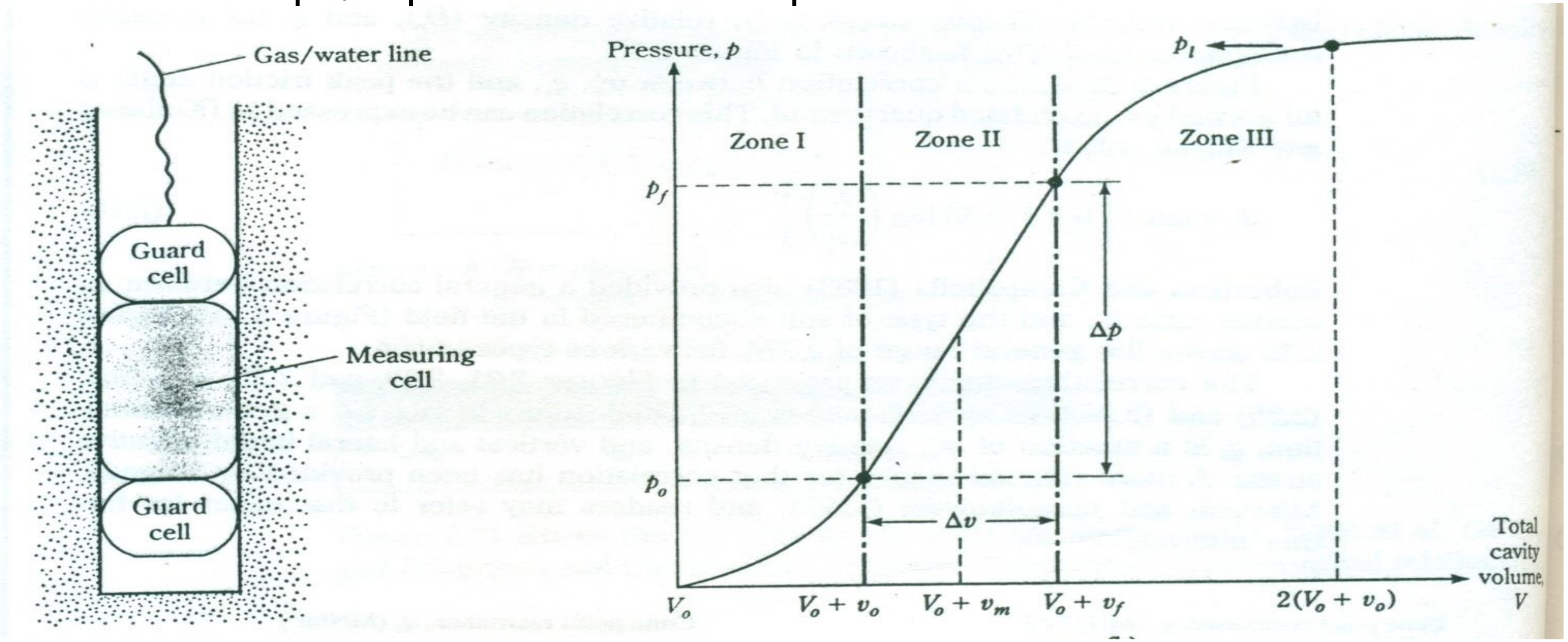
V_0 is measured and the probe is inserted into the borehole.

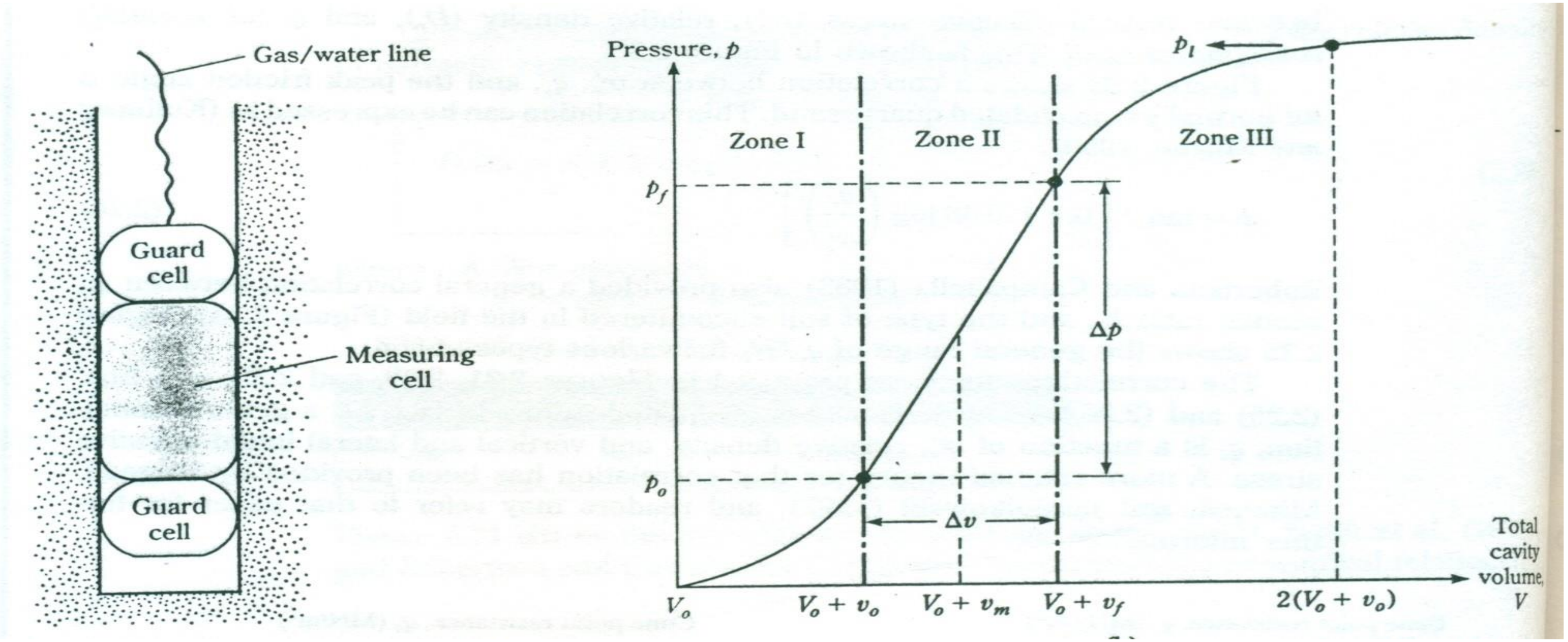
The pressure is applied in increment and the volumetric expansion of the cell is measured

Zone I: Reloading Zone and p_0 represents the in- situ total horizontal stress

Zone II: Pseudo -elastic Zone

Zone III: Plastic Zone and p_l represents the limit pressure





Pressuremeter modulus, $E_p = 2(1+\mu)(V_0 + v_m)\left(\frac{\Delta p}{\Delta v}\right)$

where $v_m = (v_0 + v_f)/2$; $\Delta p = p_f - p_0$; $\Delta v = v_f - v_o$, μ = Poisson's ratio and V_0 = measuring cell volume = 535 cm^3

Correlations

$$c_u = \frac{p_l - p_0}{N_p}$$ (Baguelin et al. 1978)

where c_u is undrained shear strength of clay

$$N_p = 1 + \ln\left(\frac{E_p}{2c_u}\right)$$

Typical values of N_p vary between 5 to 12 (average = 8.5)

$$E_p\,(kN/m^2) = 908N^{0.66}$$ For Clay

$$E_p\,(kN/m^2) = 1930N^{0.63}$$ For Sand

Ohya et al. 1982, also Kulhawy and Mayne, 1990

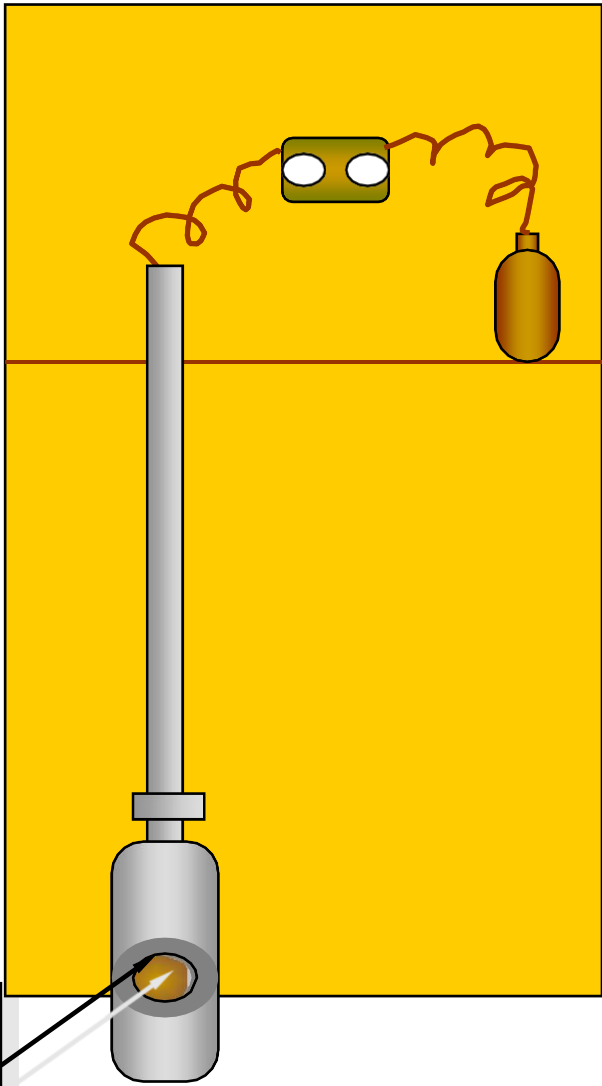
where N is field standard penetration value

Dilatometer Test

- Advance @ 20 mm/s. Test every 200- 300 mm.
- Nitrogen tank for inflating the membrane.
- Gives c_u, K_0, OCR, c_v, k, soil stiffness .
- Can identify soil (from a chart).

Similar to the cone

60 mm diameter flexible steel membrane



Marchetti (1980)

$$K_0 = \left(\frac{K_D}{1.5}\right)^{0.47} - 0.6$$

$$K_D = \frac{p_0 - u_0}{\sigma_v'}$$

$$OCR = (0.5K_D)^{1.6}$$

$$E_D\,(kN/m^2) = 34.7(p_l - p_0)$$

$$\frac{c_u}{\sigma_v'} = 0.22$$ Normally consolidated clay

p_0 is the contact stress
p_l is the expansion stress
u_0 is the pore water pressure

$$\left(\frac{c_u}{\sigma_v'}\right)_{over\ consolidated\ caly} = \left(\frac{c_u}{\sigma_v'}\right)_{normally\ consolidated\ caly} (0.5K_D)^{1.25}$$

$$E = (1 - \mu^2)E_D$$

σ_v' (or p_0') is the vertical effective overburden pressure or stress
E is the elastic modulus
K_0 is the coefficient of earth pressure at rest
μ= Poisson’s ratio

Example

A dilatometer test was conducted in a clay deposit. The ground water table was located at a depth of 2m below ground level. At a depth of 7 m below the ground level, the contact pressure (p_0) was 280 kN/m^2 and the expansion stress (p_l) was 350 kN/m^2. Determine K_0, OCR and E. Assume , μ = Poisson's ratio =0.35. Saturated and bulk unit weight is 20 kN/m^3 and 18 kN/m^3, respectively.

Types of Sampler

Vane Shear Test

Insitu or Field VST

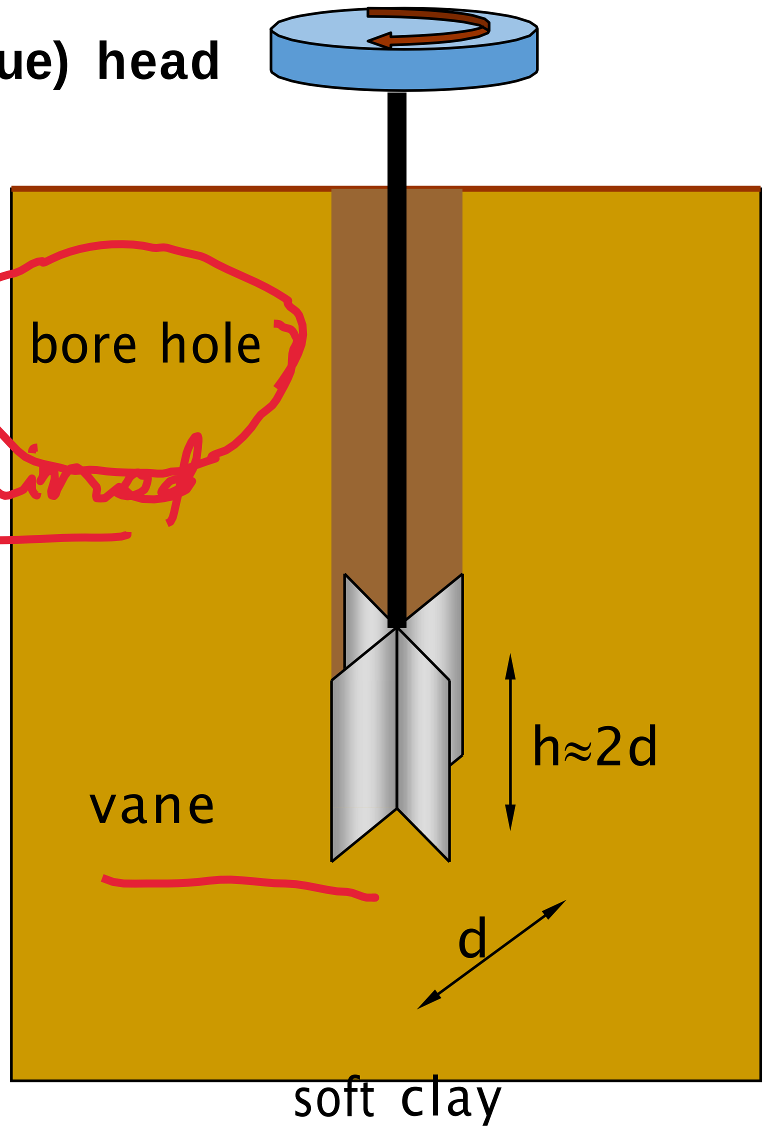
- For clays, and mainly for soft clays.
- Measure torque (T) required to **quickly** shear the vane pushed into soft clay.

∴ undrained is required

torque ➔ undrained shear strength c_u

- Typical d = 20 –100 mm.

measuring (torque) head



$$c_u = \frac{T}{\pi\left(d^2 \frac{h}{2} + \frac{d^3}{6}\right)}$$

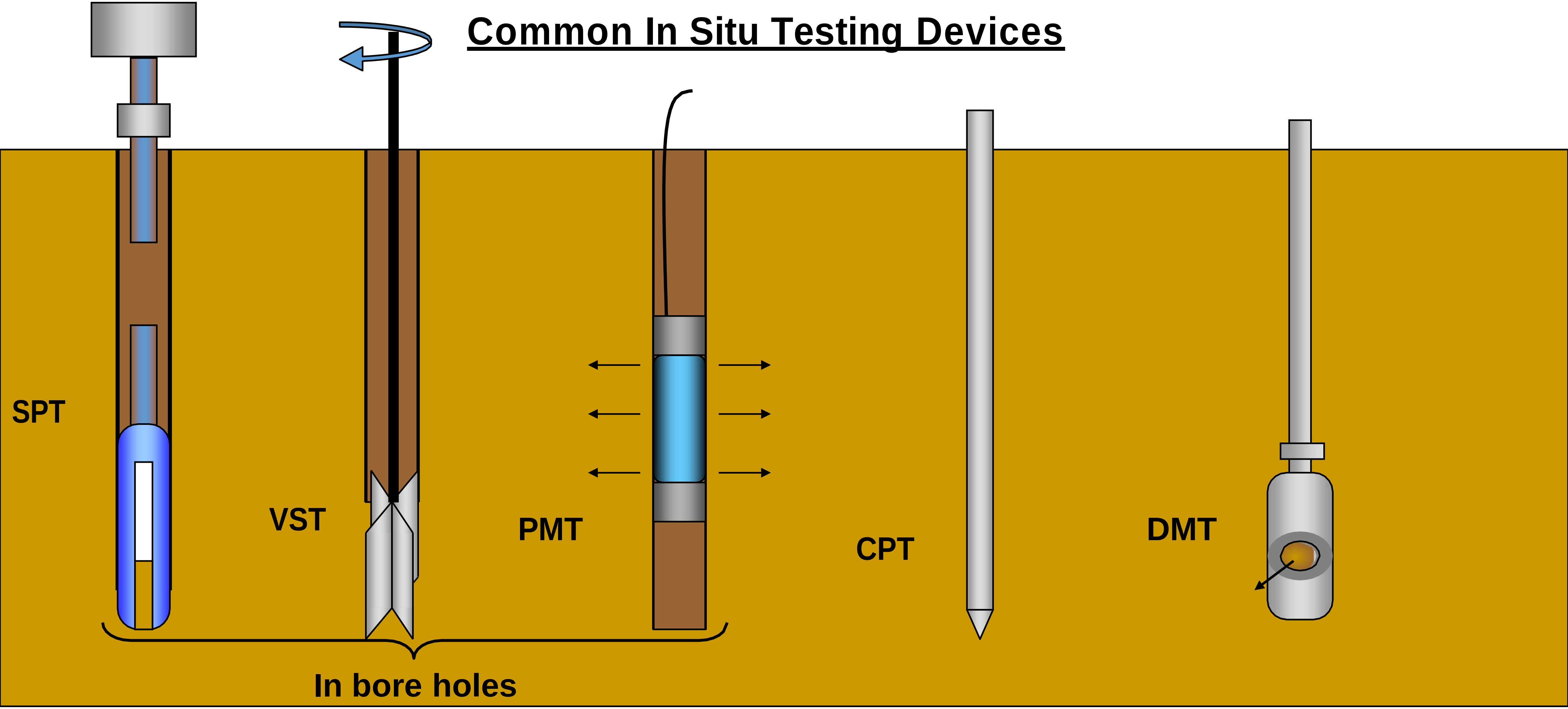
c_u = Undrained shear strength of soil

T = Torque applied

h= Height of the vane

d= diameter of the soil cylinder sheared

Common In Situ Testing Devices



N. Sivakugan

Types of Samples

- Samples of soil taken out of natural deposits for testing may be classified as:
  - ❑ Disturbed sample
  - ❑ Undisturbed sample
  - ❑ A disturbed sample is that in which the natural structure of the soil gets modified partly or fully during sampling
  - ❑ An undisturbed sample is that in which the natural structure and other physical properties remain preserved.

Disturbed but representative samples can generally be used for	Undisturbed samples must be used for
• Grain-size analysis • Determination of liquid and plastic limits • Specific gravity of soil solids • Organic content determination • Soil classification	• Consolidation test • Hydraulic conductivity test • Shear strength test

Index properties

c, ϕ

permeability

K

mv

Cc

Cv

u

Strength properties

drainage properties

Undisturbed Samples

permeability test

- Required for triaxial, consolidation tests in the lab.
- Good quality samples necessary.

$A_R < 10\%$

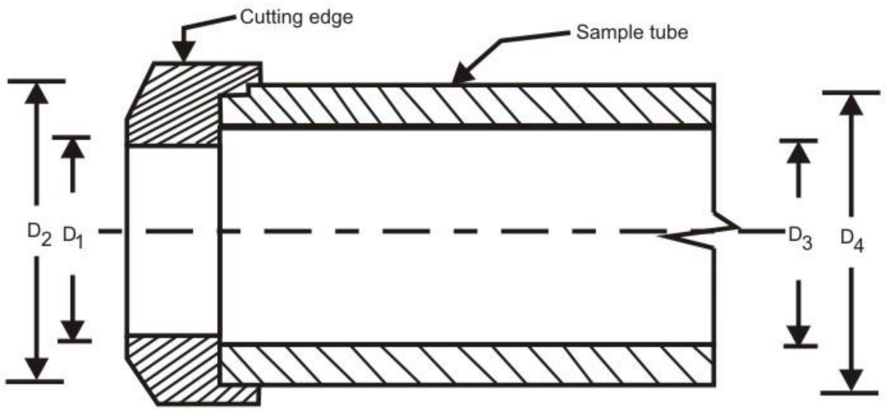
sampling tube or sampler

$$A_R = \frac{O.D.^2 - I.D.^2}{I.D.^2} \times 100\ (\%)$$

area ratio

- Thicker the wall, greater the disturbance.
- Take good care in transport and handling.

Sample Disturbance



- Inside clearance, C_i

$$C_i = \frac{D_3 - D_1}{D_1} \times 100$$

- Outside clearance, C_0

$$C_0 = \frac{D_2 - D_4}{D_4} \times 100$$

- Area ratio, A_R

$$A_R = \frac{D_2^2 - D_1^2}{D_1^2} \times 100$$

Ranjan and Rao, 2000

- According to IS: 1892 – 1979, C_i should be in between 1% to 3%
- C_0 usually lies between 0 to 2 %
- A_R should not be greater that about 20% for stiff formation, whereas for soft sensitive clay, $A_R \leq 10\%$

- The degree of disturbance of a cohesive or rock sample can be estimated by recovery ratio L_r

$$L_r = \frac{Actual\ length\ of\ recovered\ sample}{Theoretical\ length\ of\ recovered\ sample}$$

L_r = 1 (recovered length of the sample = the length sampler was forced into the stratum). Theoretically, the sample did not become compressed from friction on the tube.

L_r = 1 indicates a good recovery

L_r <1 indicates that the soil is compressed

L_r >1 indicates that the soil has swelled

Types of Samplers

- **Soil samplers are classified as:**
  - ‘Thick wall’ samplers (Split spoon sampler)
  - ‘Thin wall’ samplers (Shelby tubes)

Split Spoon Sampler

SPT

- A drive shoe attached to the lower end serves as the cutting edge. A sample head may be screwed at the upper end of split spoon.
- The standard size of the spoon sampler is of 35 mm (34.9 mm) internal and 50.8 mm external diameter.

Split Spoon Sampler

- The sampler is lowered to the bottom of the bore hole by attaching it to the drill rod. The sampler is then driven by forcing it into the soil by blows from a hammer.

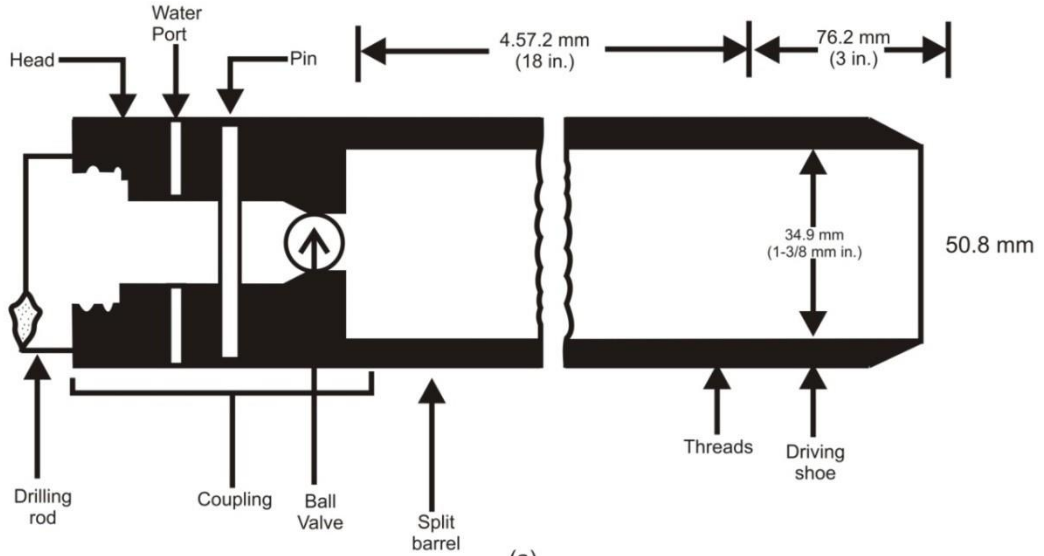
- The assembly of the sampler is then extracted from the hole and the cutting edge and coupling at the top are unscrewed. The two halves of the barrel are separated and the sample is thus exposed.

- Samples are generally taken at intervals of about 1.53 m (5 ft)

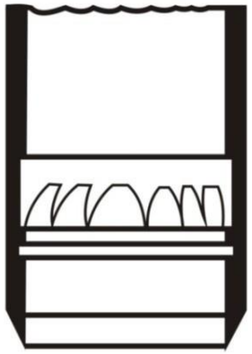
1.5m max

samples can be collect

Split Spoon Sampler



(a)



(b)

Split Spoon Sampler

- For a standard split-spoon sampler

$$A_R = \frac{(50.8)^2 - (34.9)^2}{(34.9)^2}(100) = 112\%$$

Hence the samples are highly disturbed.

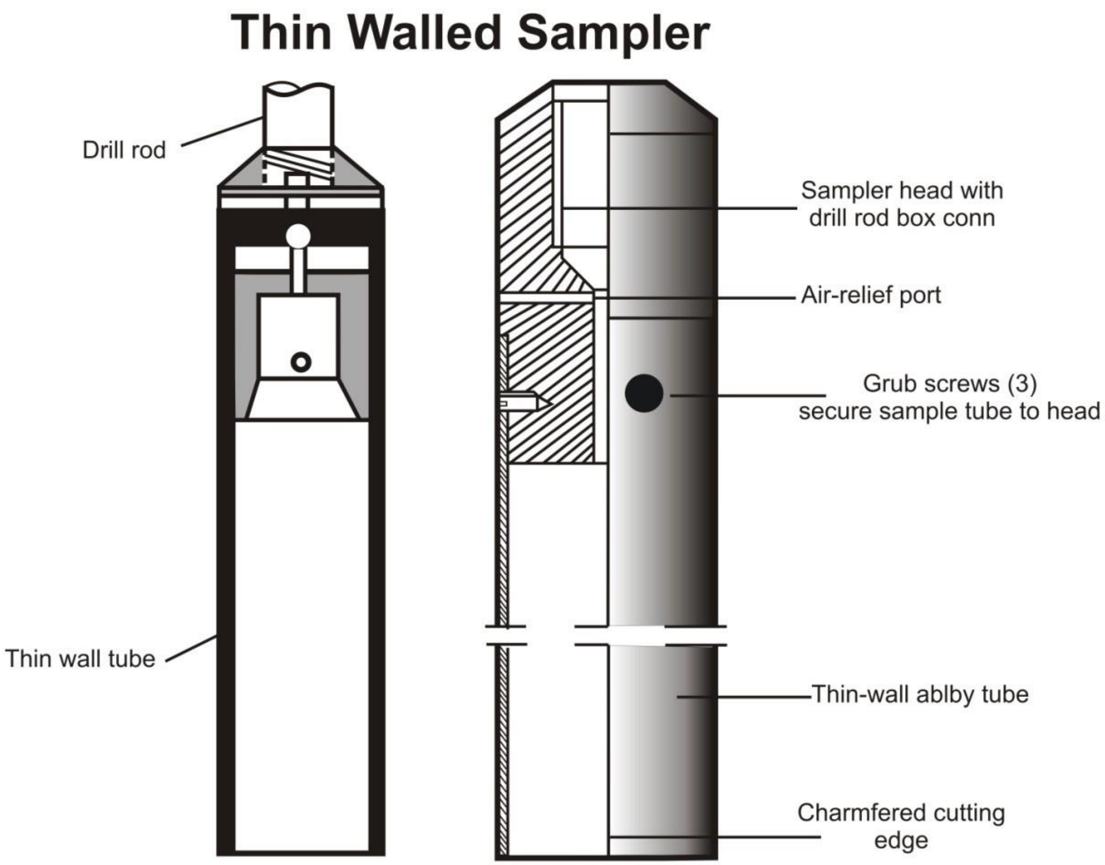
- When the material encountered in the filed is sand (particularly fine sand below the water table), a device such as a **spring core catcher** is placed inside the split spoon.

Thin Walled Sampler

- Commonly used to obtain undisturbed clayey samples.
- Outside diameter: 50.8 mm (2 in) and 76.3 mm (3 in)
- Sampler with a 50.8 mm outside diameter has an inside diameter of about 47.63 mm. The area ratio is

$$A_R = \frac{(50.8)^2 - (47.63)^2}{(47.63)^2}(100) = 13.75\%$$

Thin Walled Sampler

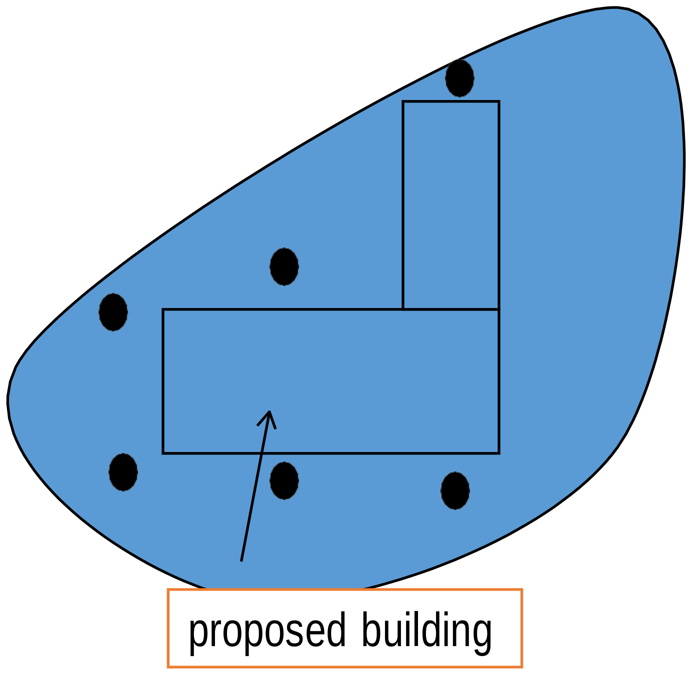


How many bore holes?

The number of bore holes depends on:

- type and size of the project
- budget for site investigation
- soil variability

Locate the bore holes where the loads are expected.



Spacing of Borings

Type of project	*Spacing (m)*
Multistory buildings	10 – 30
One-story industrial plants	20 – 60
Highways	250-500
Residential subdivision	250-500
Dams and dikes	40 – 80

- The minimum depth of boring for a building with a width of 30.5 m (100 ft) will be as follows (Sowers and Sowers, 1970)

No of stories	Boring depth
1	3.5 m
2	6.0 m
3	10 m
4	16 m
5	24 m

Depth of Borings (according to IS 1892 -1979)

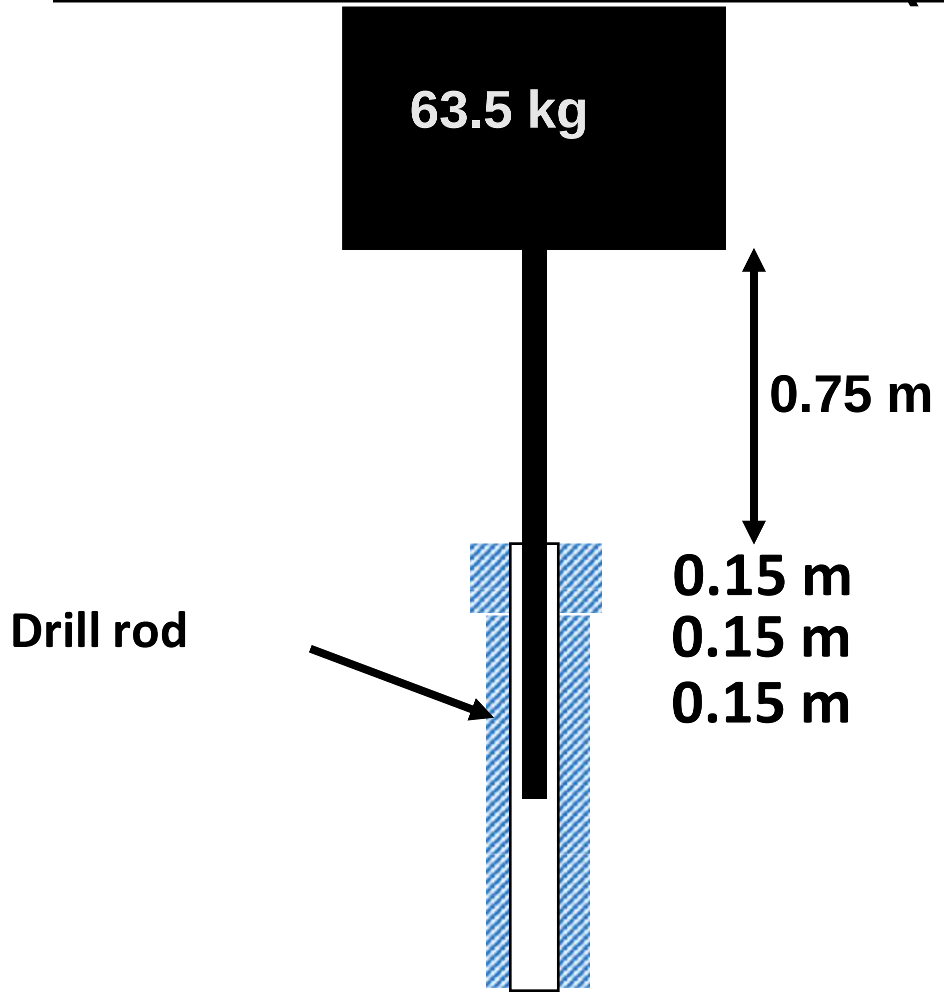
Type of foundation	Depth of boring
1. Isolated spread footing or raft	One and half times the width (B) of the foundation
2.Adjacent footings with clear spacing One and half times the length (L) of the footing less than twice the width	One and half times the length (L) of the footing
3. Pile and well foundation	To a depth of one and half times the width of structure from the bearing level (toe of pile or bottom of well).
4. (a) road cut	Equal to the bottom width of the cut
(b) Fill	Two meters below ground level or equal to the height of the fill which is greater.

Ground Water Level

- A correct indication of the general ground water level is found by allowing the water in the boring to reach an equilibrium level.
- In sandy soils, the level gets stabilized very quickly – within a few hours at the most.
- In clayey soils it will take many days for this purpose. Hence, standpipes or piezometers are used in clays and silt.

Geophysical Exploration I

Standard Penetration Test (SPT)



Number of blows for the first 150 mm penetration is disregarded due to the disturbance likely to exist at the bottom of the drill hole

The test can be conducted at every 1m vertical intervals (Not more than 1.5 m)

Number of blows = N_1

Number of blows = N_2

Number of blows = N_3

Standard penetration resistance (SPT N) = $N_2 + N_3$

Cone Penetration Test (CPT)

Dynamic cone penetration test (DCPT)

- similar to SPT; hammer driven
- using cone instead of split spoon

closed end; no samples

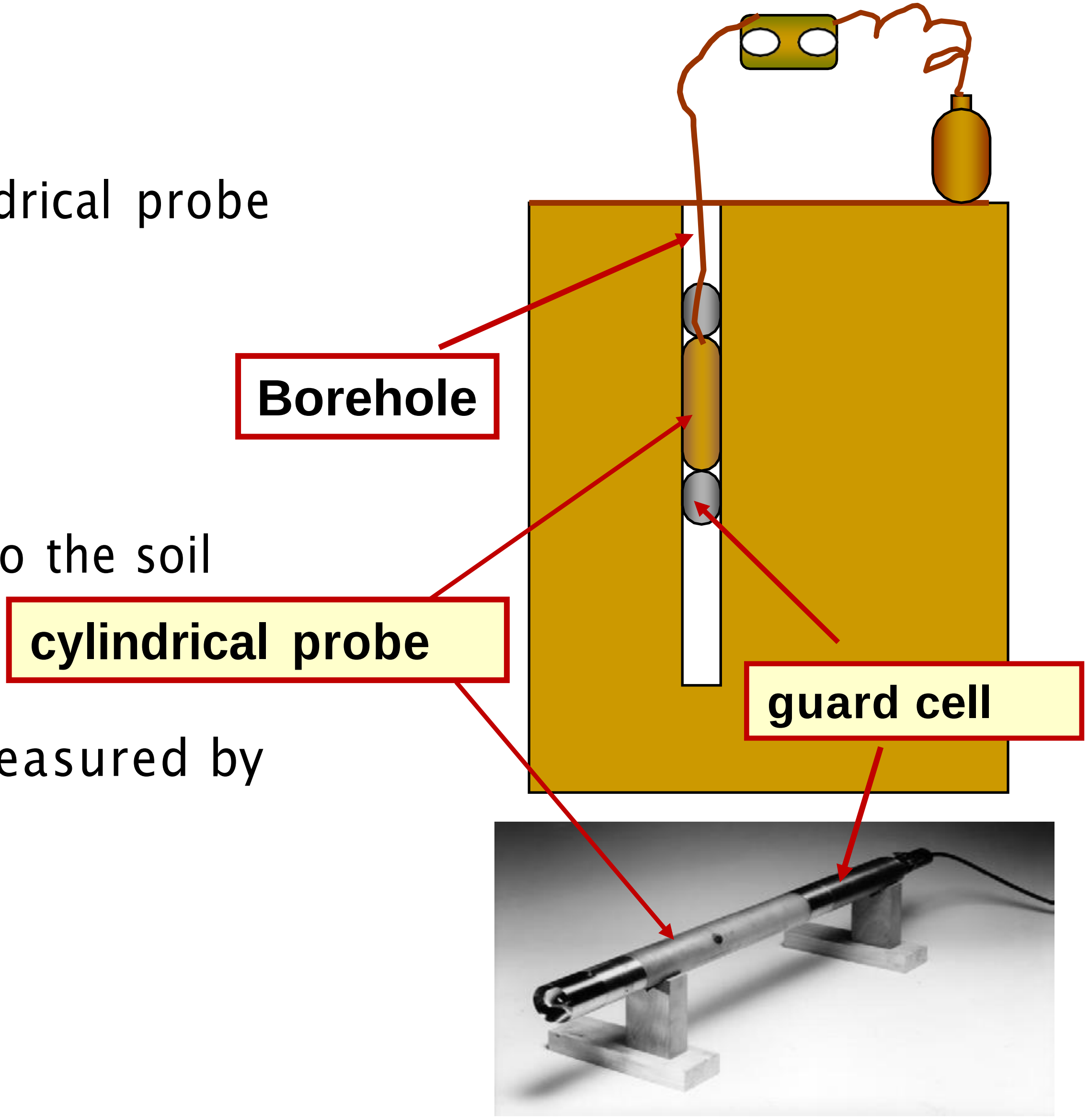
- gives blow counts @ 1.5 m depth intervals

Static cone penetration test (SCPT)

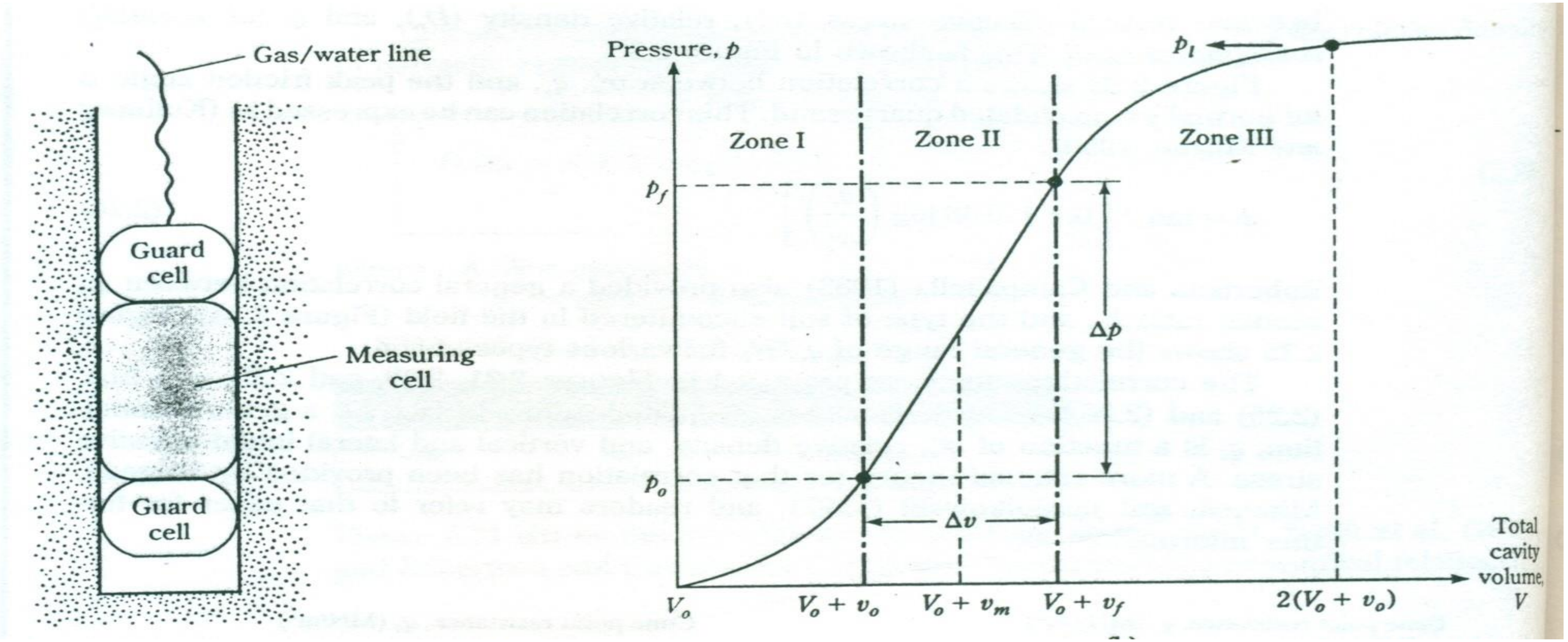
- pushed into the ground @ 1 cm/s
- gives continuous measurements

Pressuremeter Test

- The pressure meter consists of an inflatable cylindrical probe which is connected to a water reservoir.
- Expand cylindrical probe inside a bore hole.
- The probe presses against the wall of bore hole. So the soil begins to deform
- The volumetric deformation of the borehole is measured by noting the fall in water level in the water reservoir



IS: 1892-1979 describes the use of pressure meter



Pressuremeter modulus, $E_p = 2(1+\mu)(V_0 + v_m)\left(\frac{\Delta p}{\Delta v}\right)$

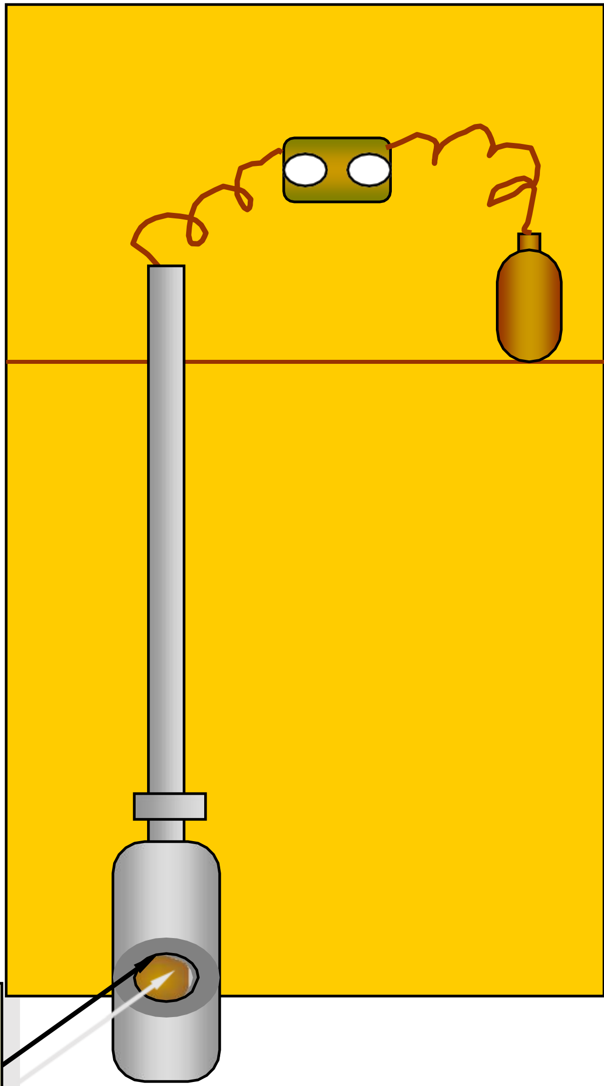
where $v_m = (v_0 + v_f)/2$; $\Delta p = p_f - p_0$; $\Delta v = v_f - v_o$, μ = Poisson's ratio and V_0 = measuring cell volume = 535 cm^3

Dilatometer Test

- Advance @ 20 mm/s. Test every 200- 300 mm.
- Nitrogen tank for inflating the membrane.
- Gives c_u, K_0, OCR, c_v, k, soil stiffness .
- Can identify soil (from a chart).

Similar to the cone

60 mm diameter flexible steel membrane



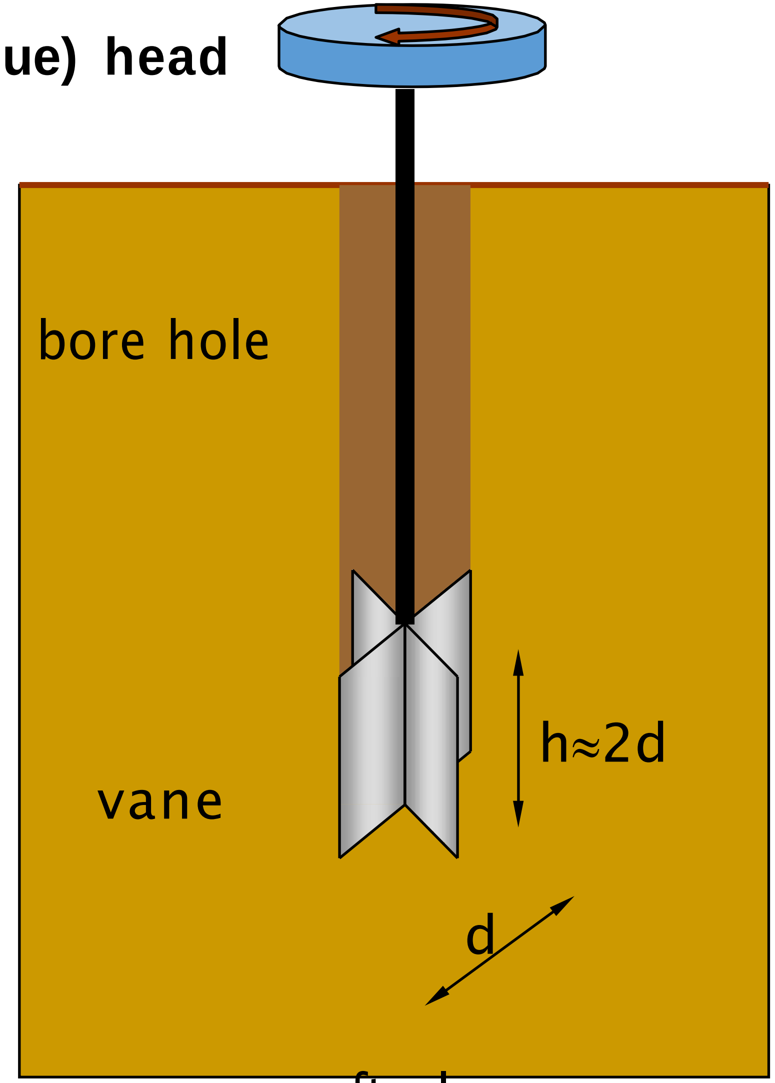
Vane Shear Test

- For clays, and mainly for soft clays.
- Measure torque (T) required to **quickly** shear the vane pushed into soft clay.

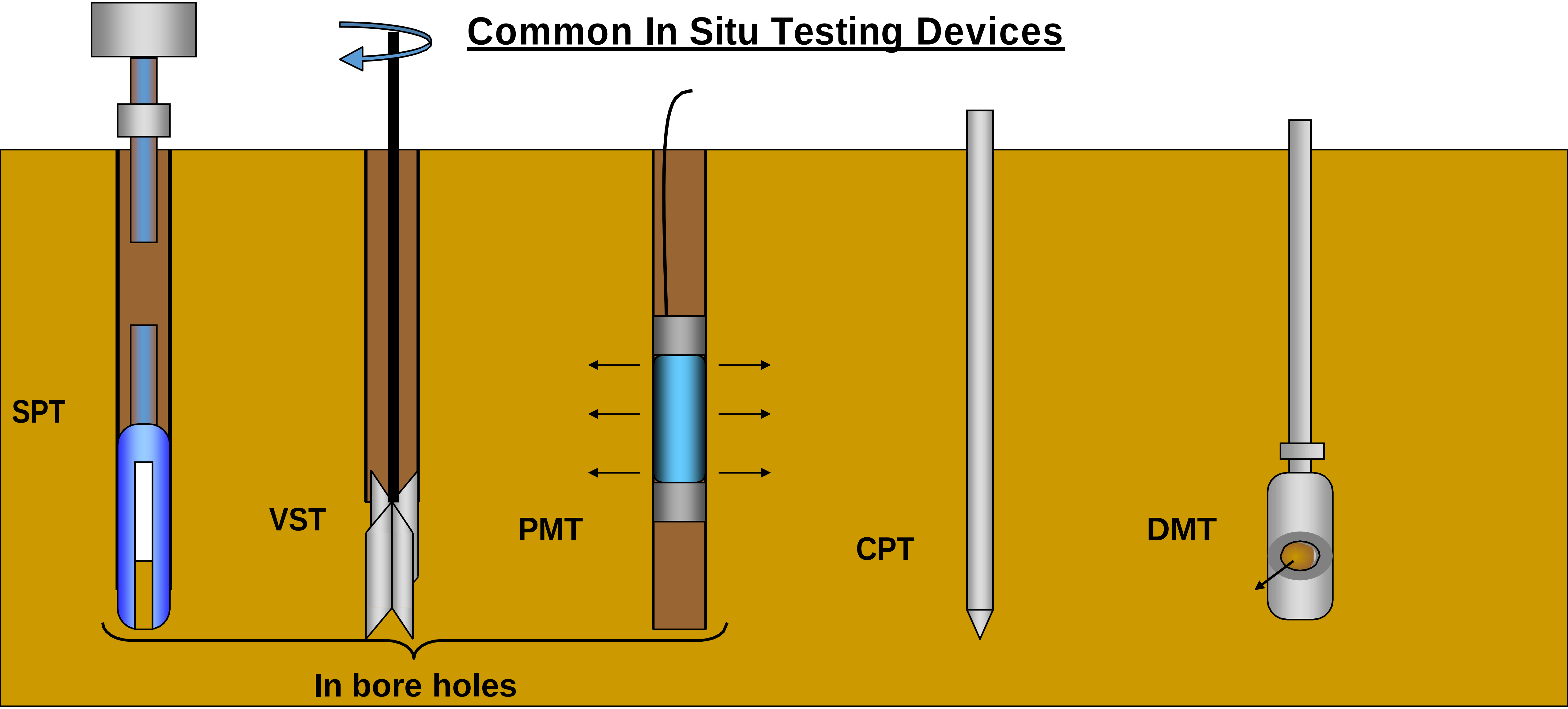
∴ undrained

torque ➔ undrained shear strength c_u

- Typical d = 20 –100 mm.



Common In Situ Testing Devices



Types of Samplers

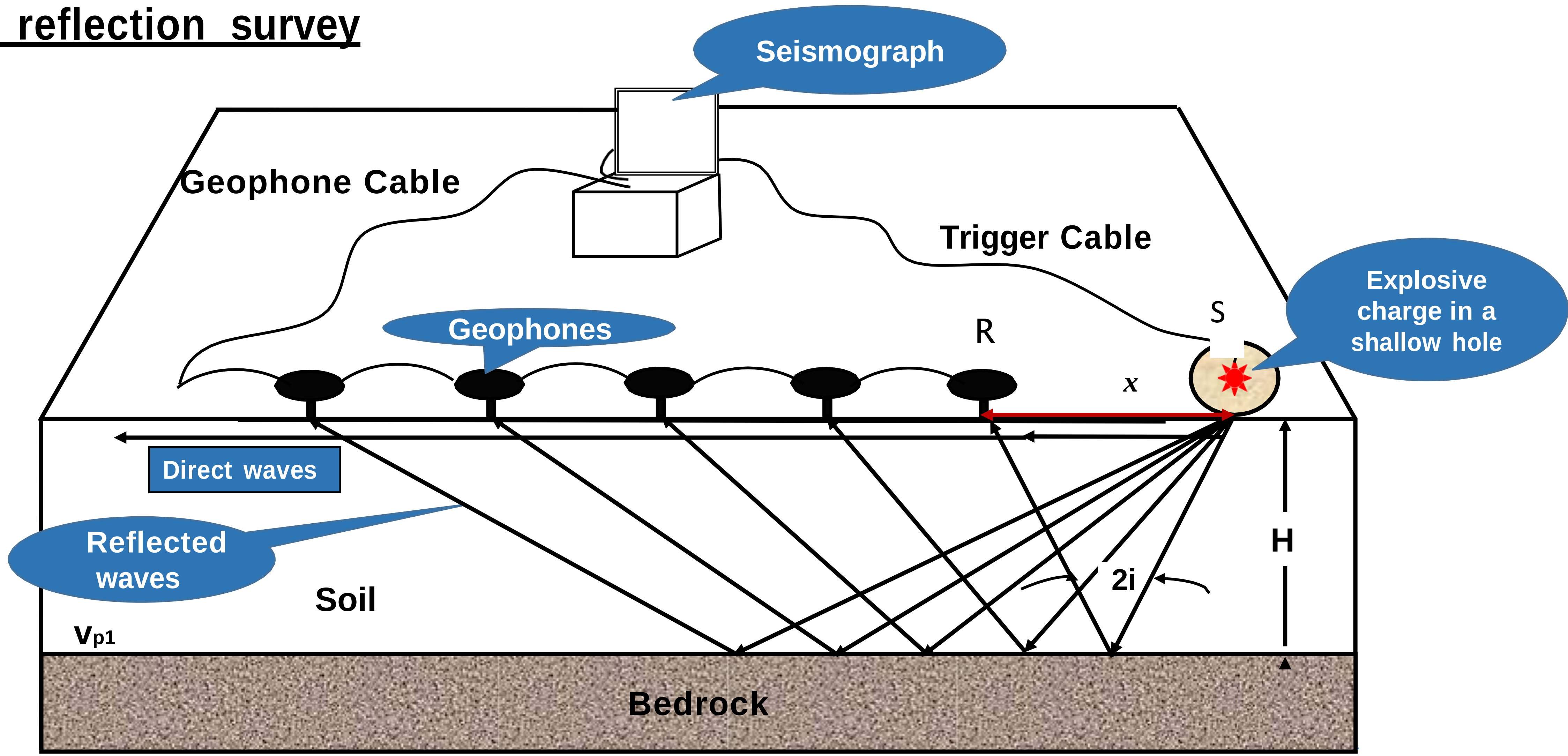
- **Soil samplers are classified as:**
  - ‘Thick wall’ samplers (Split spoon sampler)
  - ‘Thin wall’ samplers (Shelby tubes)

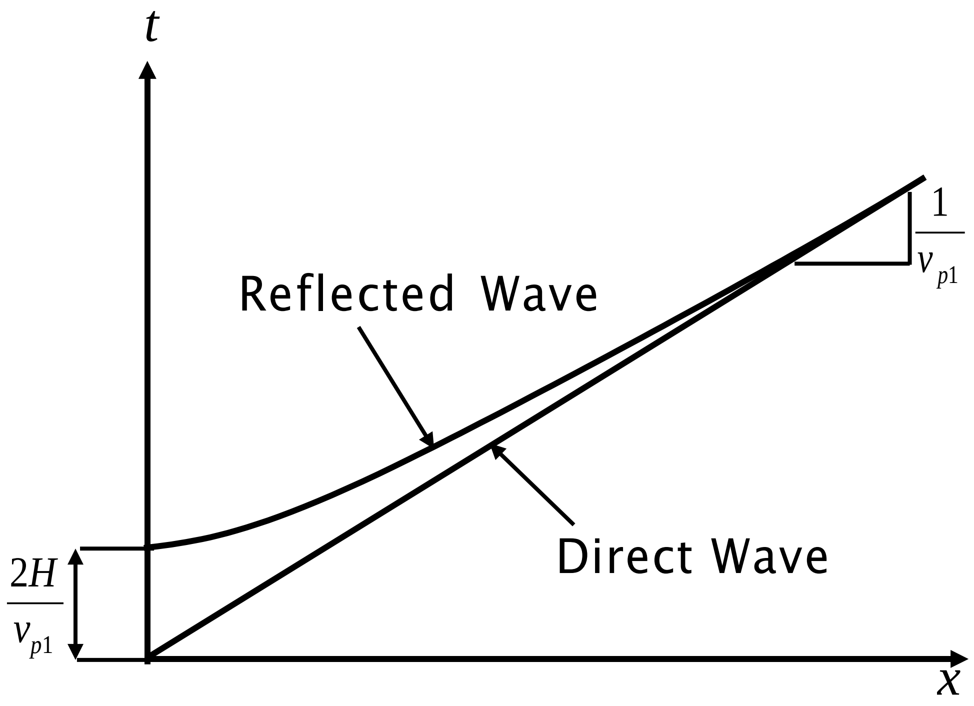
Geophysical Exploration

Geophysical Exploration

- Seismic reflection survey
- Seismic refraction survey
- Seismic Cross- hole survey

Seismic reflection survey





Some of the wave energy follows a **direct path** from S to R and arrives R at

$$t_d = \frac{x}{v_{p1}}$$

By measuring x and t_d, the p-wave velocity of the upper layer, v_{p1} , can be determined

The part of the wave that is **reflected** back toward the ground surface arrives at the receiver at

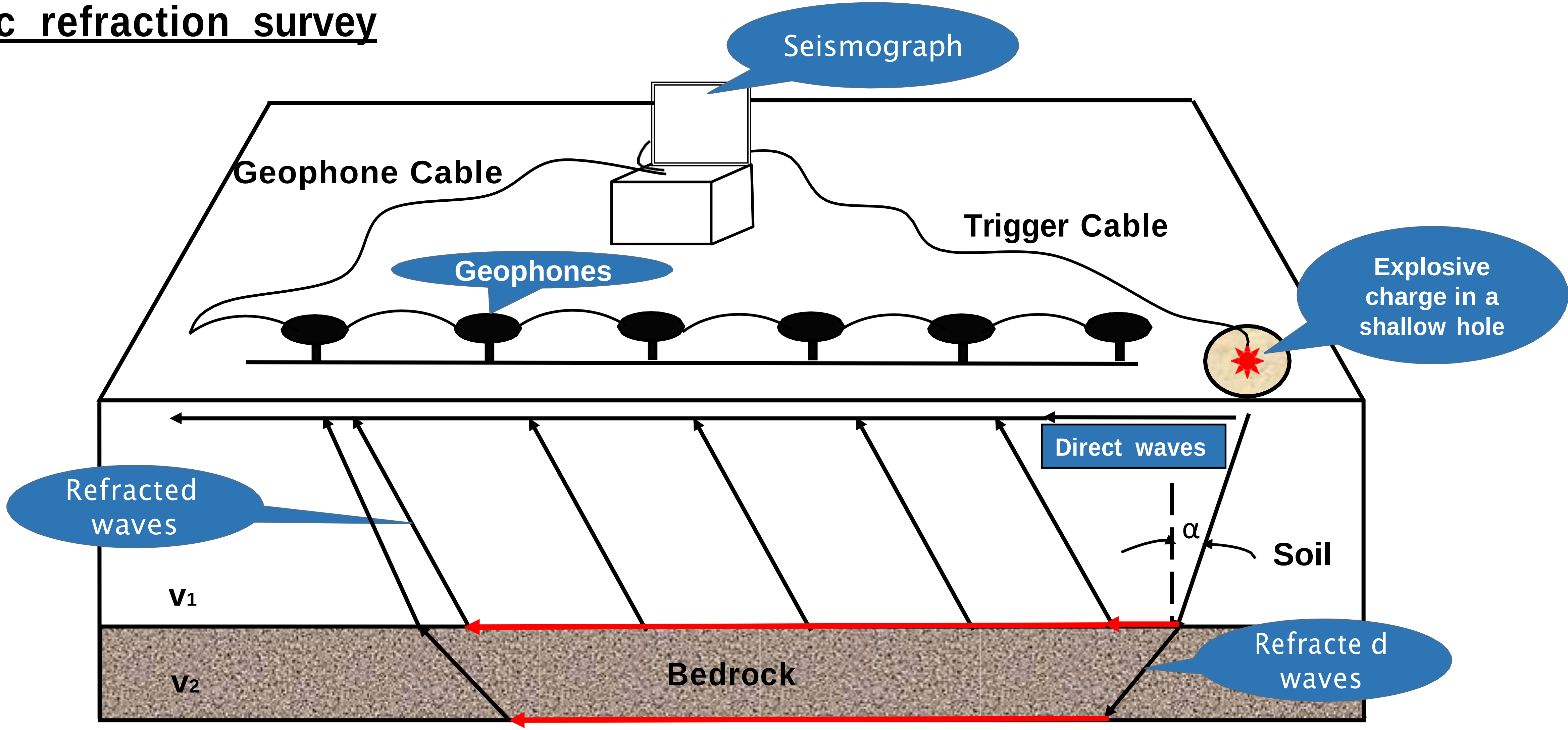
$$t_r = \frac{2\sqrt{H^2 + (x/2)^2}}{v_{p1}}$$

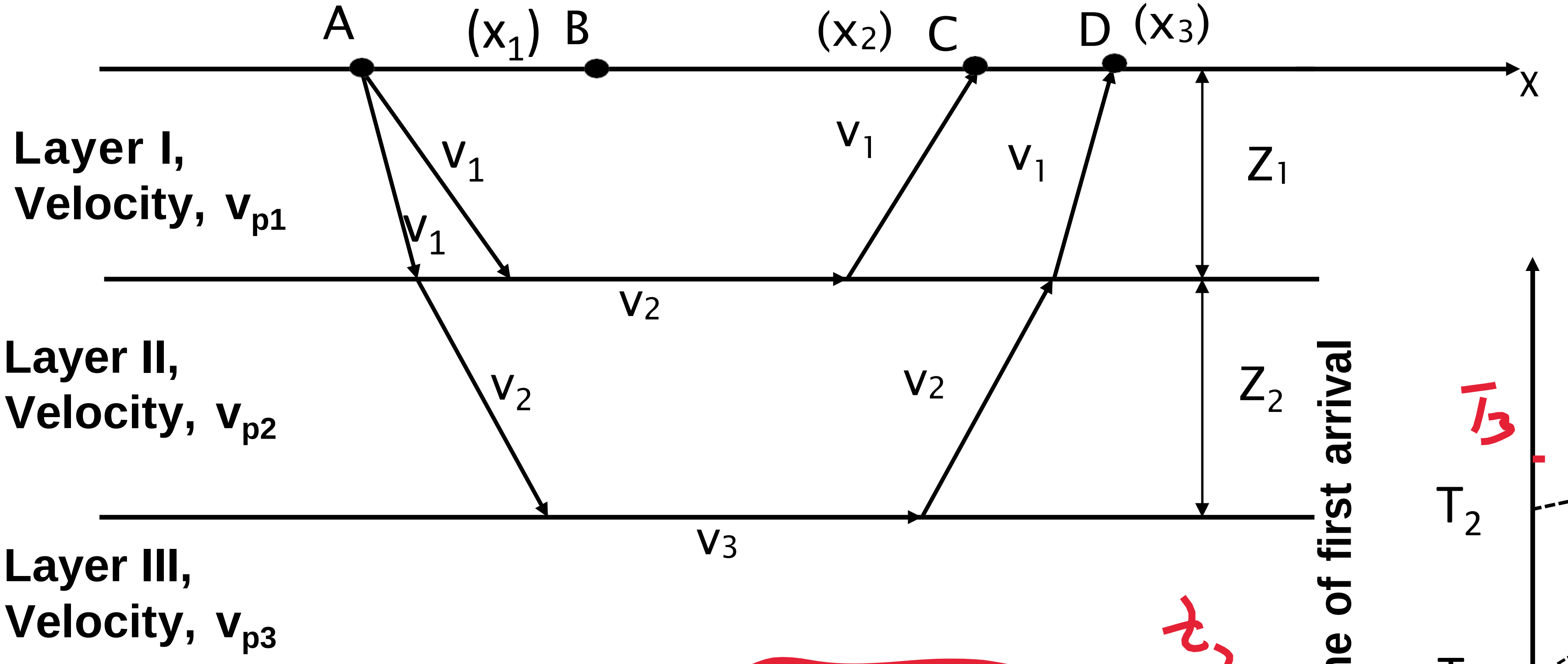
By measuring t_r and x and knowing v_{p1} from the direct wave calculation, **the thickness of the upper layer (H)** can be calculated as

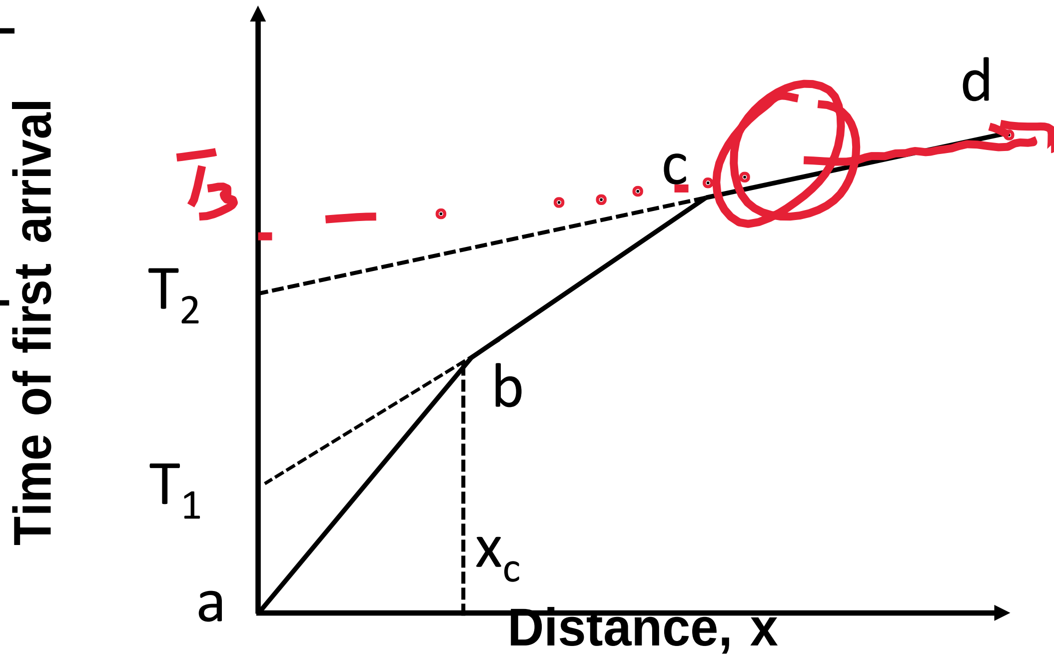
$$H = \frac{1}{2}\sqrt{t_r^2 v_{p1}^2 - x^2}$$

Geophysical Exploration II

Seismic refraction survey




A
(x1) B
(x2) C
D (x3)
x
Layer I,
Velocity, vp1
v1
v1
v1
v1
Z1
v2
Layer II,
Velocity, vp2
v2
v2
Z2
v3
Layer III,
Velocity, vp3


Time of first arrival
d
c
T2
b
T1
xc
a
Distance, x

Example

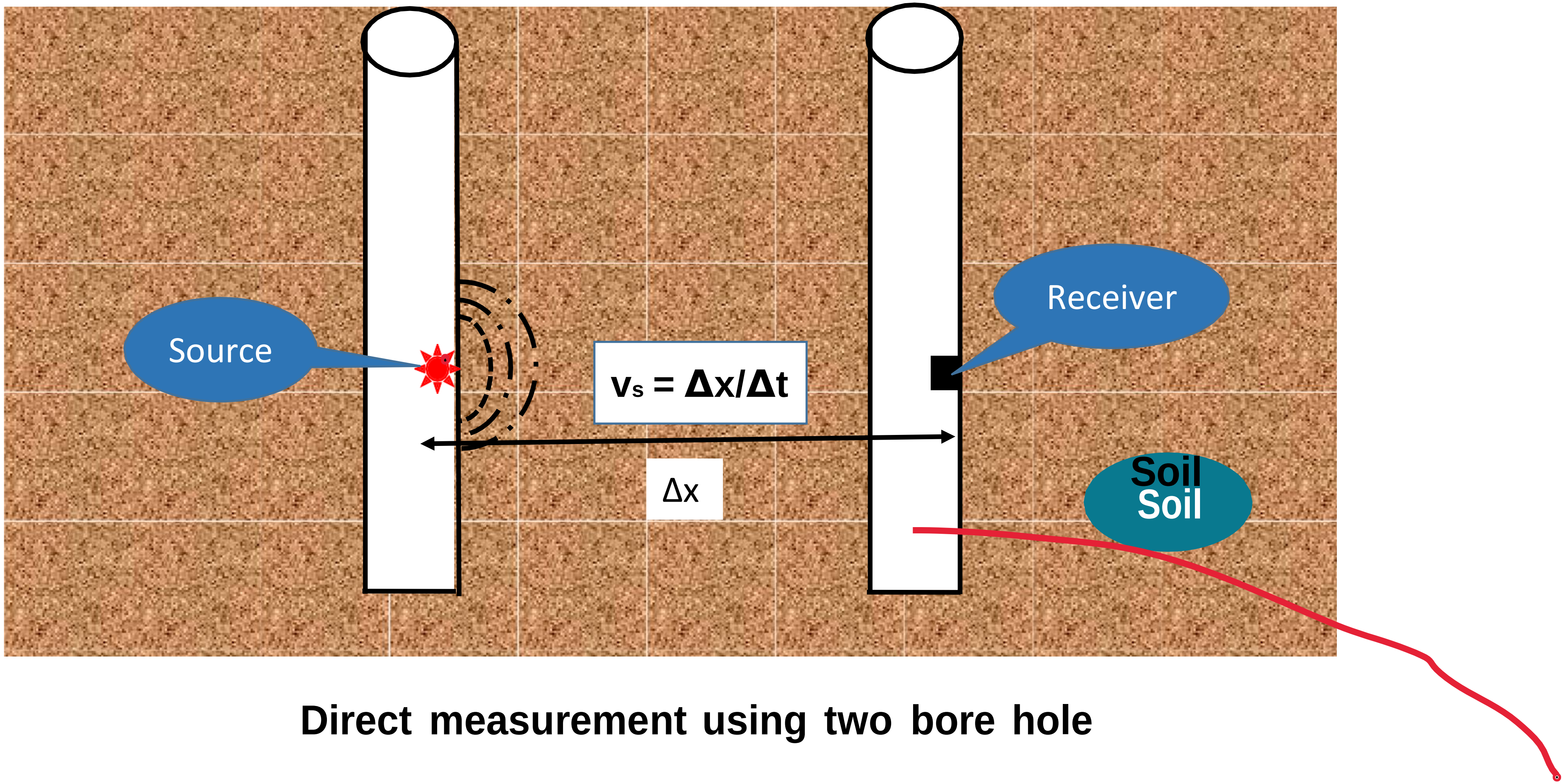
The results of a refraction survey at a site are as follows:

Distance from the source (m)	Time of first arrival of wave (msec)
2.5	5.1
5.0	10.2
7.5	15.3
10	17.0
15	19.8
20	23.9
25	27.0
30	28.0
40	31.0
50	33.7

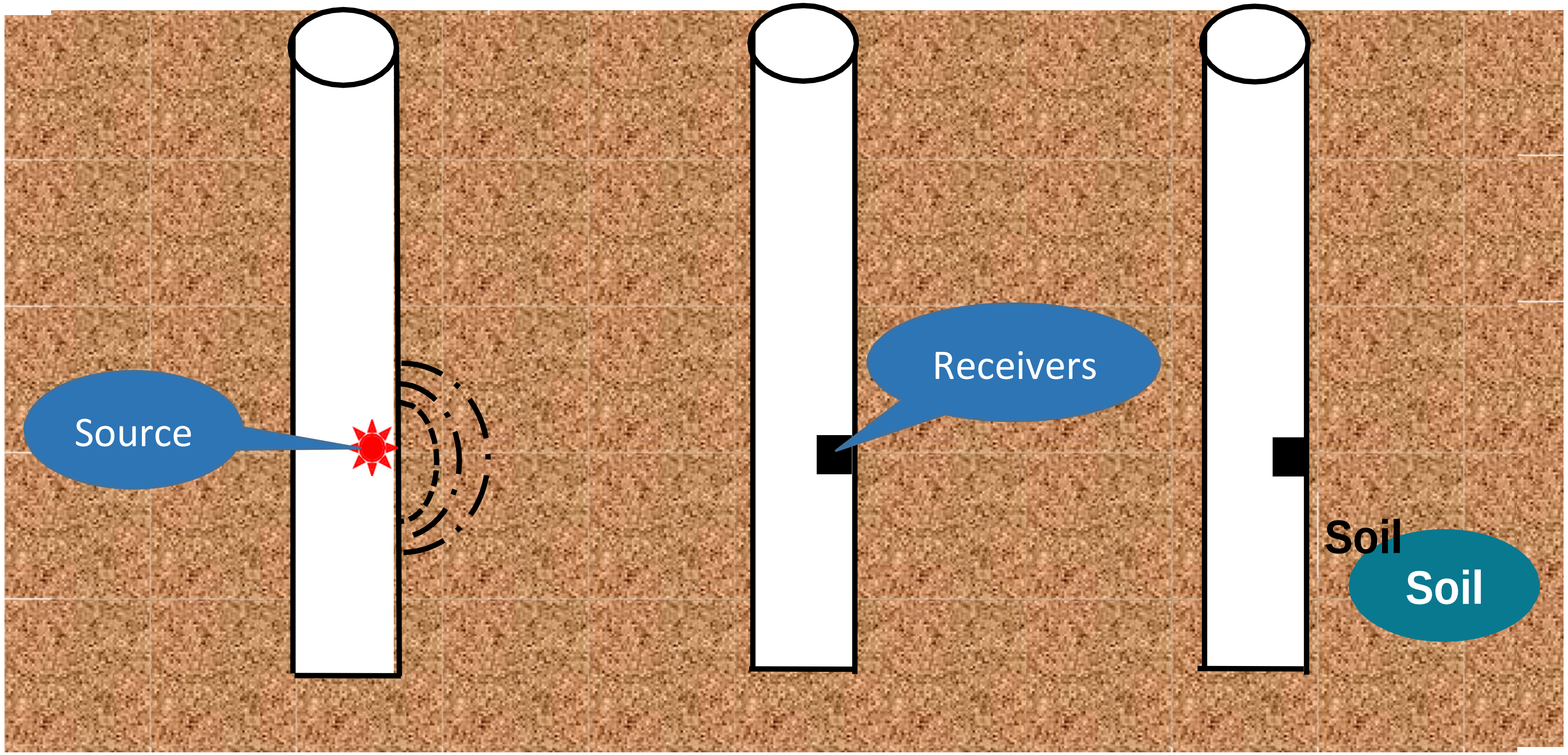
Determine the thickness of the layers and the wave velocity.

40
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
to
to
1/Vp1
1/Vp2
1/Vp3
Vp1 = —
Vp2 =
Vp3 =
z1 = — ?
z2 = — ?

Seismic cross-hole survey



Direct measurement using two bore hole



Interval measurment using three -hole configuration

secondary wave — V_s

$$G = \rho V_s^2$$

where G is the shear modulus of the soil, V_s is the shear wave velocity and ρ is the density of the soil

$$V_s = \sqrt{\frac{G}{\rho}}$$

$$V_p = \sqrt{\frac{K + \frac{4}{3}G}{\rho}}$$

where K is the bulk modulus of the soil

Primary wave