densification gradually reduces the curvature of air-water interfaces; and, finally, no curvature remains at saturation. Hence the capillary potential increases with increase of density.

iii- Effect of Temperature:

The surface tension varies inversely with temperature. A decrease in temperature increases surface tension and hence the capillary potential is reduced.

iv- Effect of Angle of Contact:

The angle of contact between the menisci and the soil particles depends on the mineral composition of soil. An increase in the angle of contact will show low degree of wetting and hence tend to decrease the curvature of the menisci and thereby increase the capillary potential of soil at that particular water content. A soil with an angle of contact greater than zero will have less attraction for water than a soil in which the particles are completely wetted.

v- Effect of Dissolved Salts:

An increase in percentage of dissolved salts in soil water increase its surface tension, and reduces the capillary potential, and hence indicate more attraction for moisture. However the effect of dissolved salts is very small.

2.6 PERMEABILITY:

Permeability of a soil is its properly which indicates the ease or difficulty with which water or any other liquid flow through soil.

A soil mass consists of discrete particles. The pore spaces between particles are all interconnected so that water is free to flow within the soil mass.

The knowledge of permeability of soil is important for the following:

1. Evaluating the amount of seepage through or beneath dams and levees and into water wells.
2. Evaluating the uplift or seepage forces beneath hydraulic structures for stability analyses.
3. Providing control of seepage velocities, so that, fine particles are not eroded from the soil mass.
4. Rate of settlement (consolidation) studies where soil volume changes occur as water is expelled from the voids.
5. Controlling seepage from sanitary landfills and hazardous liquid waste dumps.
6. Evaluating the yield from wells as a source of water supply.
7. Designing the highways sub-drainage system.
8. Designing sub-drainage for water logging and salinity control.
9. Ground water lowering (Dewatering).
10. Investigation of contaminated lands.
11. Design of landfill sites.

2.7 DARCY'S LAW:

According to Darcy's law, the velocity of flow through soil is directly proportional to the hydraulic gradient.

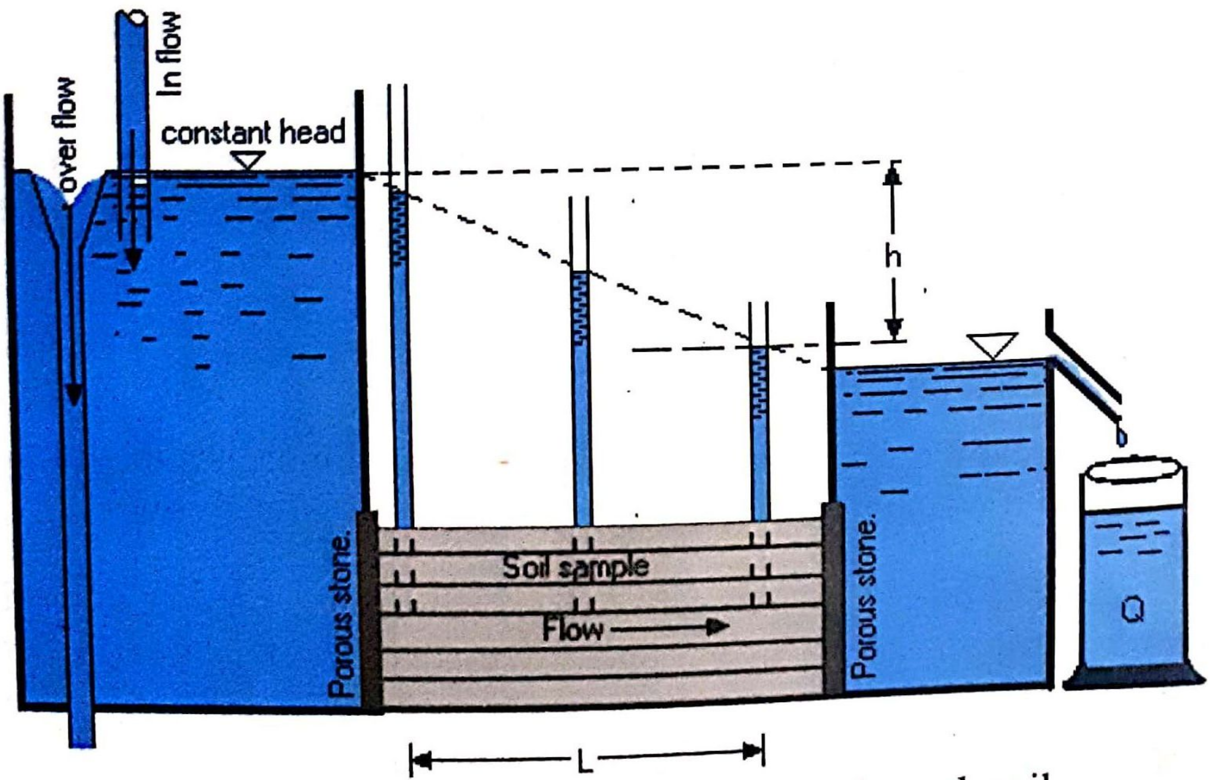

Fig: P-66. Loss of head, due to flow of water through soil.

Let us consider the Fig. *P-66*

h = difference of head.

L = length of soil between two points along the flow path where piezometers are installed.

V = velocity of flow through soil = Q/A

where:

Q is the discharge & A is the gross cross-sectional area of the soil cylinder.

i = hydraulic gradient = h/L

According to Darcy's law.

$$V \propto i$$

$$V = ki \qquad (2.7)$$

Where K is the constant of proportionality and is known as coefficient of permeability.

Assumption of Darcy's Law:

1. The continuity of the flow condition in the soil mass must be satisfied with no velocity changes taking place during the flow.

2. The flow must be with voids saturated through out the flow and no compressible air present in the voids.

3. The flow must be in a steady state. i.e., the velocity of flow must be constant at any particular section with respect to time.

4. The flow must be laminar.

2.8 FECTORS EFFECTING PERMEABILITY:

The factors, which affect the flow of a fluid through a soil mass, are discussed as under.

1. Soil grain size:

The permeability depends largely on the size of voids, which in turn depends on the size, shape and state of packing of the soil particles. Permeability appears to be proportional to the square of the effective grain size.

$$K \propto (D_{10})^2$$

For sandy soil, A.Hazen developed the following empirical equation.

$$K = C\,(D_{10})^2 \quad \text{cm/sec.} \qquad (2.8)$$

Is this equation D_{10} is the effective grain size in centimeters, with C such that K is in centimeters per second. The coefficient C varies, according to Hazen, from about 40 to 150 and the values may be taken as follows:

Table: P-68.Values of coefficient C for different grades of sand.

C	Sand (any or all of the following applies)
40-80	Very fine, well graded or with appreciable fines [(-) No.200]
80-120	Medium coarse, poorly graded; clean, coarse but well graded
120-150	Very coarse, very poorly graded, gravelly, clean.

It is quite usual that a poorly graded material will show a larger coefficient than a well-graded material, since the void spaces will be larger in poorly graded soil.

Where C = constant (range is 40 to 150, expressed as1/cm.sec)

For sandy soil $K = 100(D_{10})^2$ (C.G.S. units).

2. <u>Properties of the liquid:</u>

The permeability varies with density and viscosity of fluid flowing through the soil

a. <u>Density of the fluid:</u>

$$K \propto \gamma$$

γ = Density of fluid.

b. <u>Viscosity of the fluid:</u>

$$K \propto 1/\mu$$

Where:

μ = Absolute viscosity of fluid.

Since viscosity changes with temperature following equation may be used to find 'K_1' for any temp.

$$\frac{K}{K_1} = \frac{\mu_1}{\mu} \qquad (2.9)$$

Where:

K is co-efficient of permeability at standard temperature commonly 20 °C.

K_1 is the co-efficient of permeability at any test temperature.

μ is viscosity at standard temperature i.e., 20°C.

μ_1 is viscosity at test temperature.

3. <u>Void ratio:</u>

The effect of void ratio on permeability depends on the type of soil i.e., a clayey soil will have a much lower permeability than a sandy soil even though the void ratio and the density of the two soils may be nearly the same. The reason being the smaller size of pores (voids) offering greater resistance to flow in case of fine grained soil. A number of empirical relationships have been proposed between K and void ratio.

a- For cohesive soil – $K \propto e^2$

b- For non cohesive soils – $K \propto e^3/1+e$

c- Cassagrande equation for fine or medium clean sand is:

$$K = 0.85\ 1.4e^2\ K_{0.85}$$

Where:

K = permeability at any void ratio

$K_{0.85}$ = permeability at a void ratio of 0.85

4. <u>Soil Structure:</u>

Soil in-situ generally shows a certain amount of stratification because of which the permeability is greater in the horizontal direction than in the vertical direction. In performing laboratory permeability test, it is always advisable to use undisturbed samples.

5. <u>Degree of Saturation:</u>

An increase in the degree of saturation of a soil causes an increase in permeability.

$$K \propto S$$

Where, 'S' is degree of saturation.

6. <u>Entrapped air within the soil:</u>

Entrapped air/gases reduce the degree of saturation. Entrapped air, obstruct the flow reducing the value of coefficient of permeability. Entrapped air/gases may be due to,

i. Chemical decomposition of soil.
ii. Disintegration of rock and animal remains.
iii. Dissolved air.

According to D.W. Taylor the following simple Eq. relates the 'K' to a number of factors which influence permeability.

$$K = D_s^2 \frac{\gamma_w}{\mu} \frac{e^3}{1+e} C \qquad (2.10)$$

where:

D_S = Effective, grain size
γ_w = Density of permeant (water/fluid)
μ = Viscosity of permeant (water/fluid)
e = Void ratio
C = constant which depends on shape and arrangement of pores.

2.9 SUPERFICIAL AND SEEPAGE VELOCITY:

In a soil sample, water mores (moves) through the soil pores. The area of flow is actually, the cumulative pore area, which is difficult to determine. The total cross-sectional area of the soil cylinder is generally used for common permeability/ seepage calculations. The velocity in this case is known as superficial velocity.

If we use the area of voids, the velocity is then known as seepage velocity. However in most of the cases the general term velocity of flow is used which is based on total cross-sectional area of soil cylinder.

$Q = A \times V$ (where V is superficial velocity & A is the total cross-sectional area of soil)

$Q = A_v \times Vs$ (where Vs = seepage velocity & A_v = area of voids).

Let us now consider:

Porosity = $n = V_v/V$

For a unit thickness, $n = A_v/A$ *or* $A_v = n \times A$.

Putting the value of A_v in Eq. for Q.,

$Q = n.A.Vs$ *or* $n.A.\ Vs = A\ V$

$V = n.Vs.$ (2.11)

Since n is always less than 1 therefore V < Vs.

2.10 MEASUREMENT OF PERMEABILITY:

The co-efficient of permeability of a soil is determined by the following methods.

a- Laboratory Methods:

The co-efficient of permeability of a uniform soil deposit can be determined, using undisturbed soil samples by the following laboratory permeameters.

i- Constant head permeameter.

ii- Variable head permeameter.

The first one is suitable for relatively coarse grained (sandy) soils, while the second is recommended for fine grained (silty/clayey) soils.

b- Field Method:

When the soil deposit is non-uniform and the undisturbed samples do not represent the actual strata, the co-efficient of permeability is determined by the field pumping test. The test is very costly and time consuming and therefore is performed only when the in-situ conditions of the deposit and the importance of the project demand for the accurate measurement of the permeability. Pumping test can be performed in any of the following two ways.

i- Pumping-out test/discharge well test.
ii- Pumping-in test/recharge well test.

In case of water bearing strata discharge well test is commonly performed. However, if the permeability of a non-water bearing strata is required for any project, then a recharge well test is carried out.

2.11 CONSTANT HEAD PERMEAMETER:

It is an apparatus in which the head remains constant and the quantity of water flowing through a soil sample of known cross-sectional area and length in a given time can be measured. The permeameter is shown in the fig: P-72.

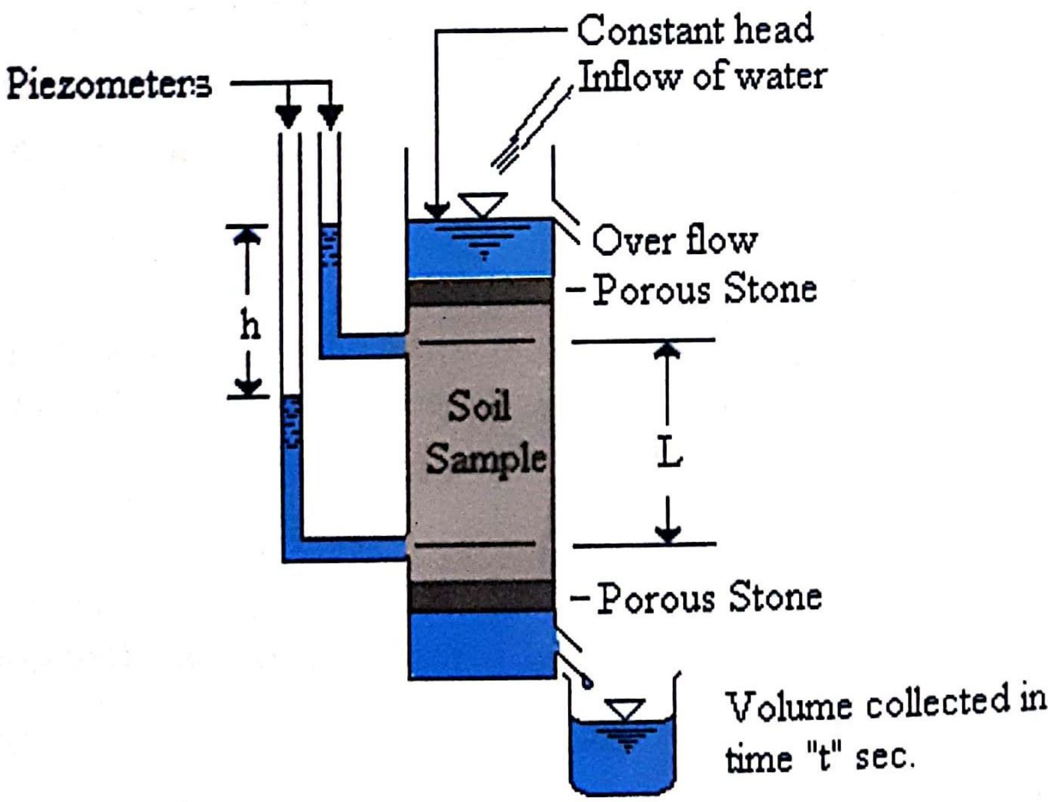

Fig: P-72. Constant head Permeameter.

Let A = Cross-sectional area of soil sample
L = Length of sample

h = drop in head between the two piezometers
l = distance between peizometers
$Vol.$ = Volume collected in time T.
T = time of test

According to DARCY'S law, velocity of flow through soil is directly proportional to hydraulic gradient.

$$V \propto i$$
$$V = K \times i$$

$$\text{Since } \; i = \frac{h}{l}$$

$$V = K \times \frac{h}{l}$$

Multiplying 'A' on both sides

$$AV = KA\frac{h}{l}$$

$$Q = KA\frac{h}{l}$$

$$\text{Since } \quad Q = \frac{Vol.}{Time}$$

$$\frac{Vol.}{T} = KA\frac{h}{l}$$

$$K = \frac{Vol. \times l}{AhT} \qquad (2.12)$$

All the quantities on the right hand side of the equation are measured during the test, hence K is determined.

In highly impervious soil the quantity of flow is small and accurate measurement of its value is not possible. Therefore the constant head permeameter is mainly applicable to relatively previous soil such as sands and gravel.

2.12 VARIABLE HEAD PERMEAMETER:

Variable head permeameter is used to find the permeability of relatively less permeable soil i.e., fine grained soil (silt and clay). A stand pipe of small cross-sectional area is used, such that a very small amount of flow through the soil sample gives a significant drop of head in the stand pipe. Since the measurement of drop of head is taken during the test, it is also known as falling head permeameter. Consider the permeameter shown in the fig: P-74.

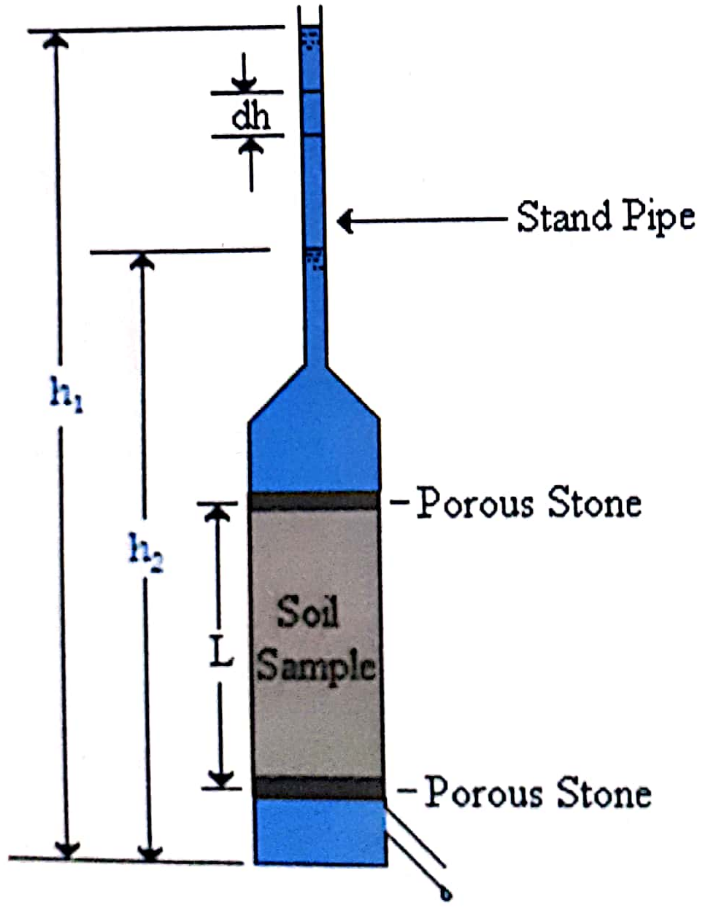

Fig: P-74. Falling/Variable head permeameter.

Let a = cross-sectional area of the stand pipe.
A = cross-sectional area of soil sample.
L = Length of sample.

h_1= Initial head at time t_1.

h_2= Final head at time t_2.

dh = the drop in head in time dt.

Velocity of fall of water level in the stand pipe $V = -dh/dt$ (-ve sign indicates a fall of head).

$$V = -\frac{dh}{dt}$$

Multiplying by 'a' on both sides

$$Va = -a \times \frac{dh}{dt}$$

$$Q = -a \times \frac{dh}{dt} \qquad Q = Discharge = Velocity \times area$$

$$KAi = -a \times \frac{dh}{dt}$$

$$KA \times \frac{h}{L} = -a \times \frac{dh}{dt}$$

$$\frac{KA}{aL}\, dt = -\frac{dh}{h}$$

Integrating the above equation.

$$\frac{KA}{aL}\int_{t_1}^{t_2} dt = \int_{h_1}^{h_2} -\frac{1}{h}\, dh$$

$$\frac{KA}{aL}(t_2 - t_1) = (-l_n h_2 + l_n h_1)$$

$$\frac{KA}{aL} \times t = l_n \times \frac{h_1}{h_2}$$

$$K = 2.303\,\frac{aL}{At}\log_{10}\frac{h_1}{h_2} \qquad (2.13)$$

All the quantities on the right hand side of the equation, are measured during the test, hence K is determined.

2.13 FIELD DETERMINATION OF PERMEABILITY:

When the soil conditions in the field are non-uniform, laboratory tests do not give accurate value of co-efficient of permeability. In such cases full scale pumping test gives reliable results. There are two types of pumping test.

i- Discharge Well (Pumping-out Test)

If water is pumped out of the test well, it is called discharge well pumping test. The method is extensively used by water supply Engineers.

A certain quantity of water Q, is continuously pumped out of the test well. Depending on soil properties, after a period of few days to fortnight, the ground water flow to the well is stabilized i.e. steady state of flow is attained and the depression funnel or cone of the lowered ground water table around the well is established. The cone of depression is observed by means of the observation wells spaced around the test well. At least two observation wells are needed to calculate the coefficient of permeability of soil.

The depression line or draw down curve moves up gradually and ultimately touches the original ground water table, and forms, a circle around the test well known as the circle of influence.

In foundation engineering the important problem is the draw down of the ground water table, which is necessary to get the dry foundation pit to start the construction work.

ii- <u>Recharge Well (Pumping-in Test)</u>

When water is pumped into the well from an out side source, it is called a recharge well test. All the procedure is similar to discharge well method, except an inverted cone of depression is developed

2.14 THEORY OF ORDINARY PERFECT WELLS (DUPUIT THIEM'S THEORY):

For the derivation of an analytical equation for the discharge Q of the well or the permeability of soil K, following assumptions are made.

1. The soil is homogeneous, uniform and porous medium of infinite areal extent.

2. The well takes the ground water from the entire thickness of the permeable water bearing stratum.

3. There exists an unconfined, uniform, steady, laminar and radial ground water flow to the cylindrical well from a concentric boundary.

4. For small inclination of the free surface of the ground water gravity flow system, the streamlines can be taken as horizontal.

5. The horizontal velocity is independent of depth.

6. The hydraulic gradient is equal to the slope of the tangent at any point on the depression curve, of the free ground water table.

7. The coefficient of permeability K of the soil is constant at all times and at all places.
8. The well is being pumped continuously at a uniform rate until the flow of water to the well is stabilized.