Introduction

In soil mechanics and foundation, engineering, you must know how much water is flowing through a soil in unit time. This knowledge is required to design earth dams, determine the quantity of seepage under hydraulic structures, and dewater before and during the construction of foundations.

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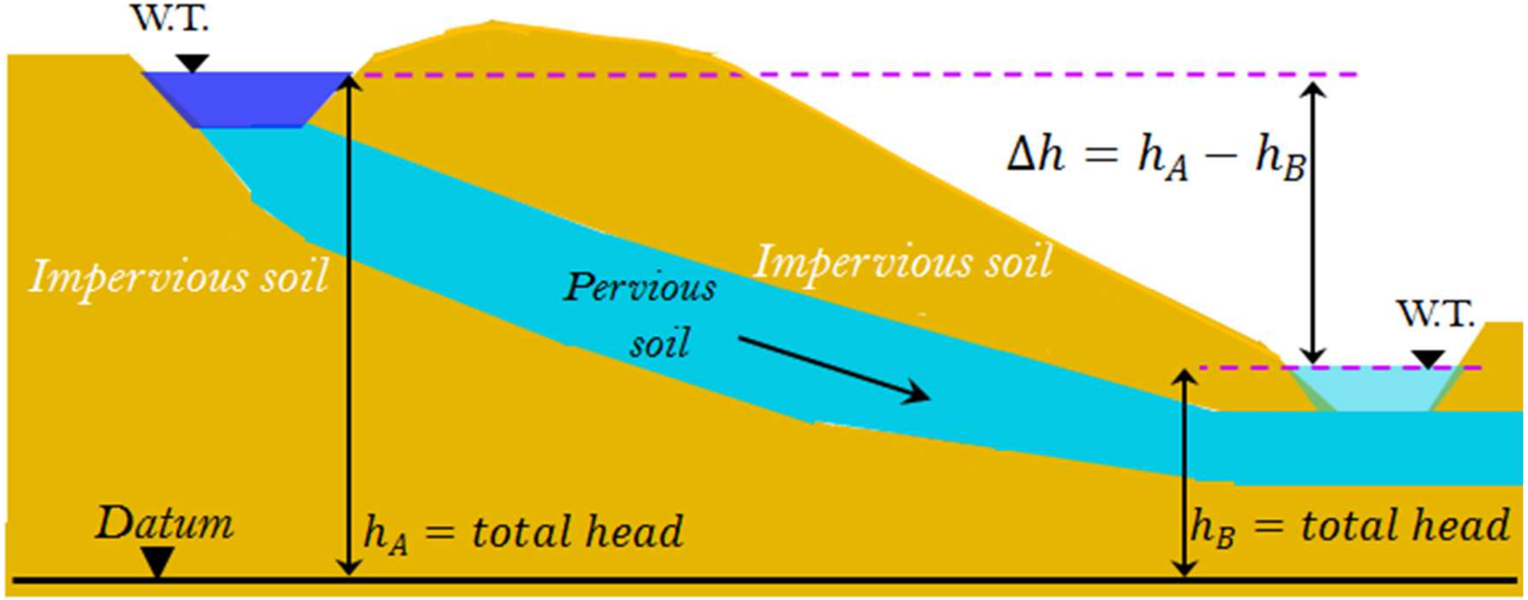
Soil Permeability

Permeability is defined as a capacity of soil to allow water passes through it i.e. quantity of flowing for a unit of soil surface under a pressure of 1 unit hydraulic gradient.

Soil Permeability

- Soils are permeable due to the existence of interconnected voids through which water flow from points of high energy to points of low energy.



Soil Permeability

- *A soil is highly pervious when water can flow through it easily. (Gravels)*
- *In an impervious soil, the permeability is very low and water cannot easily flow through it. (Clays)*
- *Rocks are impermeable*
- *The study of the flow of water through permeable soil media is important in soil mechanics.*

Importance of Permeability

The following applications illustrate the importance of permeability in geotechnical design:

- Permeability influences the rate of settlement of a saturated soil under load.
- The design of earth dams is very much based upon the permeability of the soils used.
- The stability of slopes and retaining structures can be greatly affected by the permeability of the soils involved.
- Filters made of soils are designed based upon their permeability.

Factors Affecting Permeability of Soils

The following factors affect the permeability of soils

1) Particle size
2) Void ratio of soil.
3) Properties of pore fluid.
4) Shape of particles.
5) Structure of soil mass.

Factors Affecting Permeability of Soils

The following factors affect the permeability of soils

6) Degree of saturation.
7) Absorbed water.
8) Entrapped air and organic impurities in water.
9) Temperature.
10) Stratification of soil

Factors Affecting Permeability of Soils

1. Particle size

The Permeability varies approximately as the square of grain size. It depends on the effective diameter of the grain size (D_{10})

2. Void ratio

Increase in the void ratio increases the area available for flow hence permeability increases for critical conditions.

Factors Affecting Permeability of Soils

3. Properties of pore fluid.

Pore fluids are fluids that occupy pore spaces in a soil or rock. Permeability is directly proportional to the unit weight of pore fluid and inversely proportional to viscosity of pore fluid.

Factors Affecting Permeability of Soils

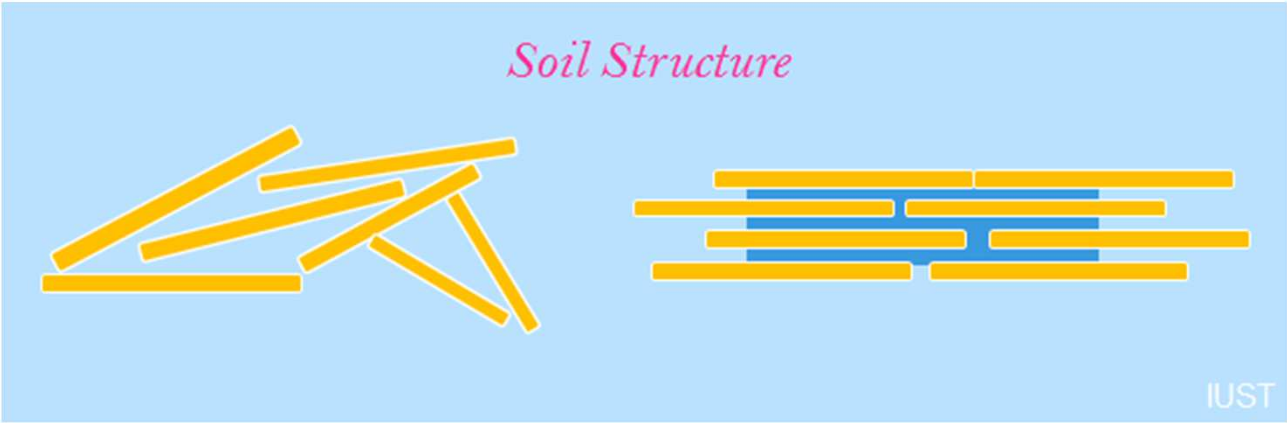
4. Shape of particles

Permeability is inversely proportional to specific surface e.g. as angular soil have more specific surface area compared to the round soil therefore, the soil with angular particles is less permeable than soil of rounded particles.

Factors Affecting Permeability of Soils

5. Structure of soil mass

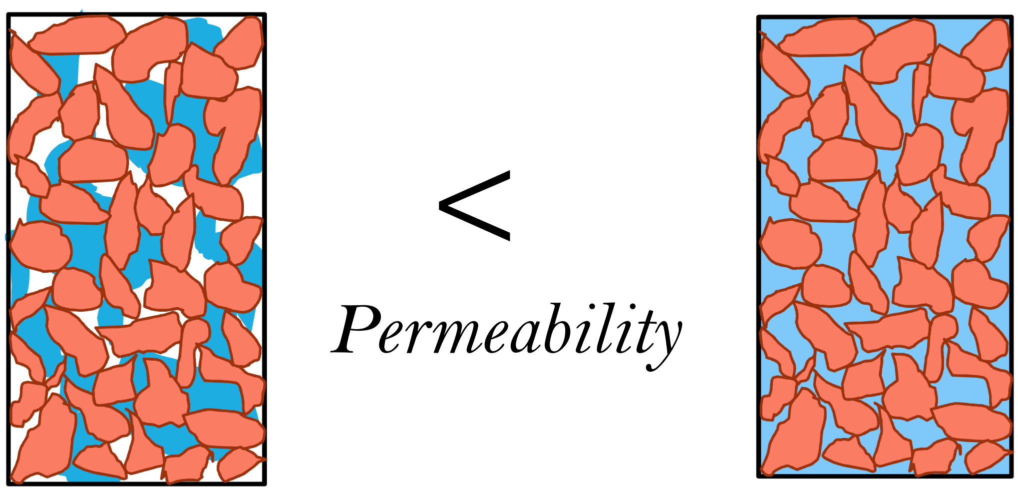
For same void ratio the permeability is more for flocculent structure as compared to the dispended structure



Factors Affecting Permeability of Soils

6. Degree of saturation

The permeability of partially saturated soil is less than that of fully saturated soil.



Factors Affecting Permeability of Soils

7. Adsorbed Water

Adsorbed Water means a thin microscopic film of water surrounding individual soil grains. This water is not free to move and hence reduces the effective pore space an thus decreases coefficient of permeability.

Factors Affecting Permeability of Soils

8. Entrapped air and organic impurities

The organic impurities and entrapped air obstruct the flow and coefficient of permeability is reduce due to their presence.

Air or water pore

Factors Affecting Permeability of Soils

9. Temperature

As the viscosity of the pore fluid decrease with the temperature , permeability increases with temperature , as unit weight of pore fluid does not change much with change in temperature.

Factors Affecting Permeability of Soils

10. Stratification of soil

Stratified soils are those soils which are formed by layer upon layer of the earth or dust deposited on each other. If the flow is parallel to the layers of stratification , the permeability is max. while the flow in Perpendicular direction occur with min. permeability.

Water Flow

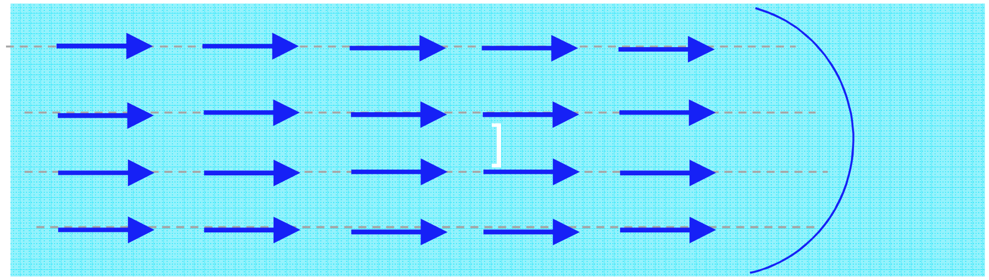
The water flow is divided into two categories:

1) Laminar flow

2) Turbulent flow

Water Flow

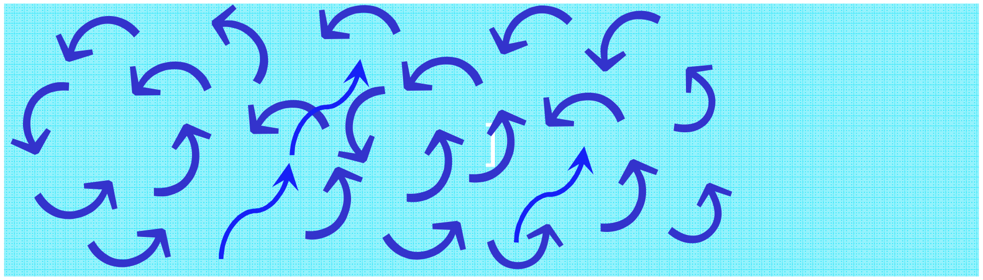
Laminar flow indicates that each water particle follows a definite path and never crosses the path of another particle.



Laminar flow

Water Flow

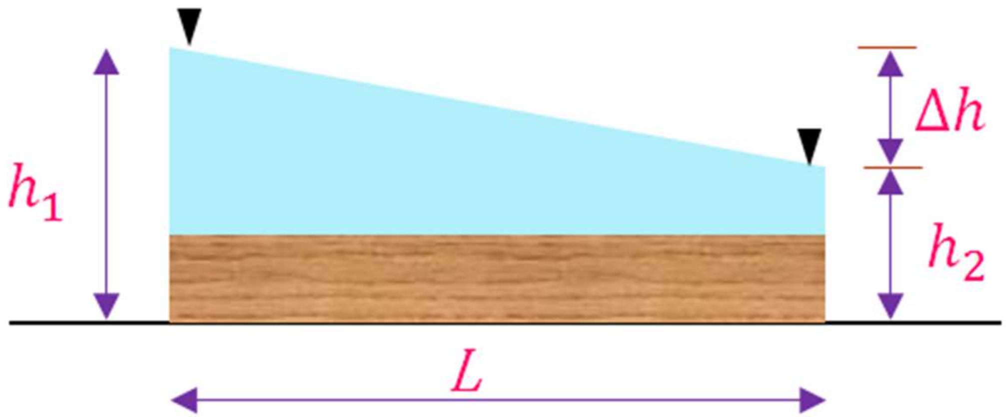
Turbulent flow indicates a random path of irregular and twisted movement.



Turbulent flow

Hydraulic Gradient

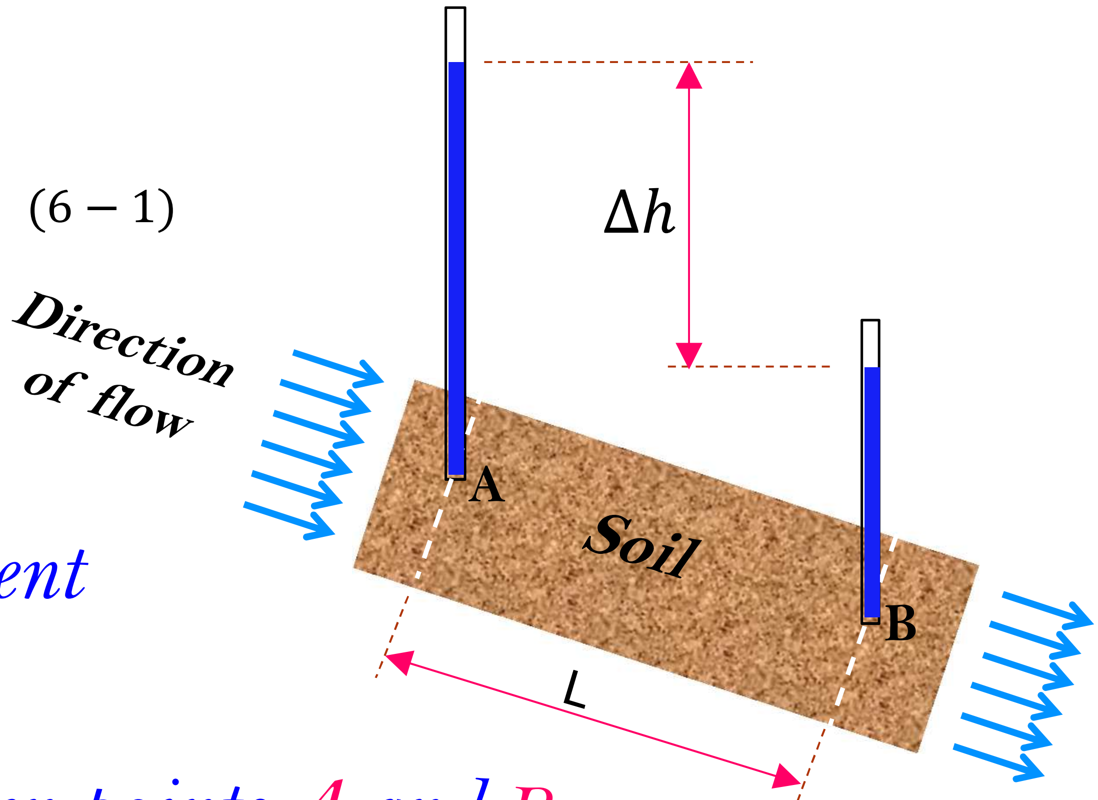
*Water below a **GWT** surface is usually flowing under a hydraulic gradient, defined as the slope of the free water surface in the direction of flow.*



Hydraulic Gradient

The hydraulic gradient is expressed as

$$i = \frac{\Delta h}{L} \qquad (6-1)$$



where:

i = *hydraulic gradient*

Δh = *the head loss*

L = *distance between points A and B*

Darcy's Law

Henry Darcy (1803-1858), Hydraulic Engineer. His law is a foundation stone for several fields of study

Darcy's Law demonstrated experimentally that for laminar flow conditions in a saturated soil, the rate of flow or the discharge per unit time is proportional to the hydraulic gradient

Darcy's Law

Darcy(1856) stated that the flow of water through porous media is directly proportional to the head loss and inversely proportional to the length of flow path. This may be written as:

$$v = k\left(\frac{\Delta h}{L}\right) \quad or \quad v = k\, i \qquad (6-2)$$

where :

k = permeability coefficient or hydraulic conductivity

v = discharge velocity (average velocity)

Darcy's Law

Discharge velocity (average velocity), is the quantity of total water flowing in unit time, (q) through a unit gross cross-sectional area, (A) of soil at right angles to the direction of flow.

$$v = \frac{q}{A} \quad (6-3)$$

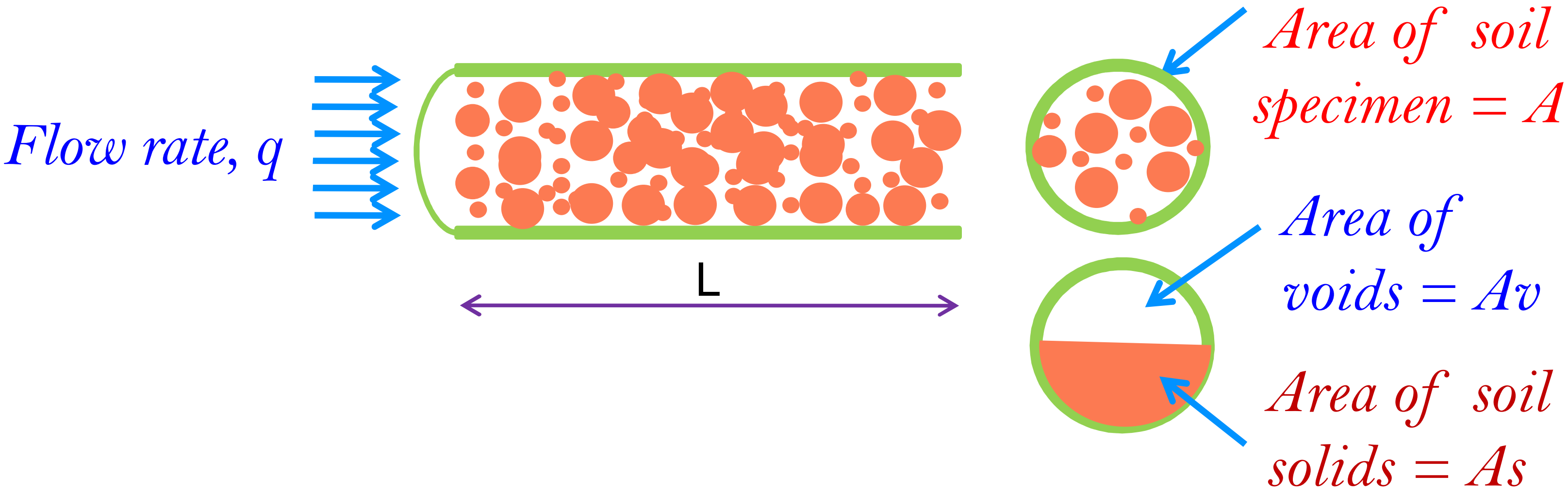
Range of Validity of Darcy's Low

Darcy's type of flow is stable in character as long as the four basic conditions are always satisfied:

- The steady state is laminar flow
- Hundred percent saturation
- Flow fulfilling continuity conditions
- No volume changes occur during or as a result of flow.

Seepage Velocity

The discharge velocity based on the gross cross sectional area of the soil. However, the actual velocity of water (that is the seepage velocity) through the void spaces is greater than v.



Seepage Velocity

A relationship between the discharge velocity and the seepage velocity:

If the quantity of water flowing through the soil in unit time is q, then

$$q = A\,v = A_v\,v_s$$

where

v_s = *seepage velocity*

A_v = *area of void in the cross section of the specimen*

Seepage Velocity

An estimate of actual velocity, vs referred to as the seepage velocity can be made by considering the following equation:

$$A\,v = A_v\,v_s$$

$$v = \frac{A_v}{A}\,v_s$$

$$v = n\,v_s \qquad (6-4)$$

Range of Validity of Darcy's Law

Darcy's type of flow is stable in character as long as the four basic conditions are always satisfied:

- The steady state is laminar flow with no changes in hydraulic gradient
- Hundred percent saturation and no air bubbles in the soil voids,
- Flow fulfilling continuity conditions
- No volume changes occur during or as a result of flow.
- The total cross sectional area of soil mass is considered.

Hydraulic Conductivity

Permeability is also known as hydraulic conductivity.

Hydraulic conductivity, marked as K, or K-values, is one of the principal and most important soil hydrology (hydraulic) characteristic (parameter) and it is an important factor in water transport in the soil and is used in all equations for groundwater (subsurface water) flow.

Hydraulic Conductivity

- *The value of hydraulic conductivity varies widely for different soils.*
- *The hydraulic conductivity of unsaturated soils is lower and increases rapidly with the degree of saturation.*

Hydraulic Conductivity

- *The coefficient of permeability also varies with temperature, upon which the viscosity of the water depends.*
- *The coefficient of permeability can also be represented by the equation*

$$k_{20^o} = \frac{\eta_T}{\eta_{20^o}} k_T \qquad (6-5)$$

where

$\eta_i = viscocity\ of\ water\ at\ temperature\ t\ and\ 20^\circ$

The Value of Hydraulic Conductivity

- *Typical value for saturated soils are given in the following table:*

Soil type	K , cm/sec.
Clean gravel	100 – 1.0
Coarse sand	1.0 – 0.01
Fine sand	0.01 – 0.001
Silty clay	0.001 – 0.00001
Clay	< 0.00001

Empirical Relation for K

- Several empirical equation for estimating k have been proposed in the past .

Some of these are:

For uniform sand

$$k\ (cm\ /\ \sec) = cD_{10}^{2} \qquad (6-6)$$

where:

c = a constant that varies from 1 to 1.5

D_{10} = the effective size, in mm

Empirical Relation for K

For dense or compacted sand

$$k\ (cm\ /\sec) = 0.35 D_{15}^{2} \qquad (6-7)$$

For medium to fine sand

$$k = 1.4 e^{2} k_{0.85} \qquad (6-8)$$

where

k = hydraulic conductivity at a void ratio e

k 0.85 = the corresponding value at a void ratio of 0.85.

Hydraulic Conductivity (K)

- *Hydraulic Conductivity, k, is a measure of soil permeability*
- *k is determined in the lab using two methods:*
  - *Constant-Head Test*
  - *Falling-Head Test*
- *K is usually expressed in cm/sec*
- *Hydraulic conductivity is also known as the coefficient of permeability*

Determination of Coefficient of Permeability

Constant – Head Test

The permeability test is a measure of the rate of the flow of water through soil.
In this test, water is forced by a known constant pressure through a soil specimen of known dimensions and the rate of flow is determined.
This test is used primarily to determine the suitability of sands and gravels for drainage purposes, and is made only on remolded samples

Determination of Coefficient of Permeability

Constant – Head Test

- The constant head test is used primarily for coarse-grained soils
- This test is based on the assumption of laminar flow where k is independent of i (low values of i)
- This test applies a constant head of water to each end of a soil in a "permeameter"

Determination of Coefficient of Permeability

Constant – Head Test

- ASTM D 2434
- In this type of laboratory setup, the water supply at the inlet is adjusted in such a way that the difference of head between the inlet and the outlet remains constant during the test period. After a constant flow rate is established, water is collected in a graduated flask for a known duration.

Determination of Coefficient of Permeability

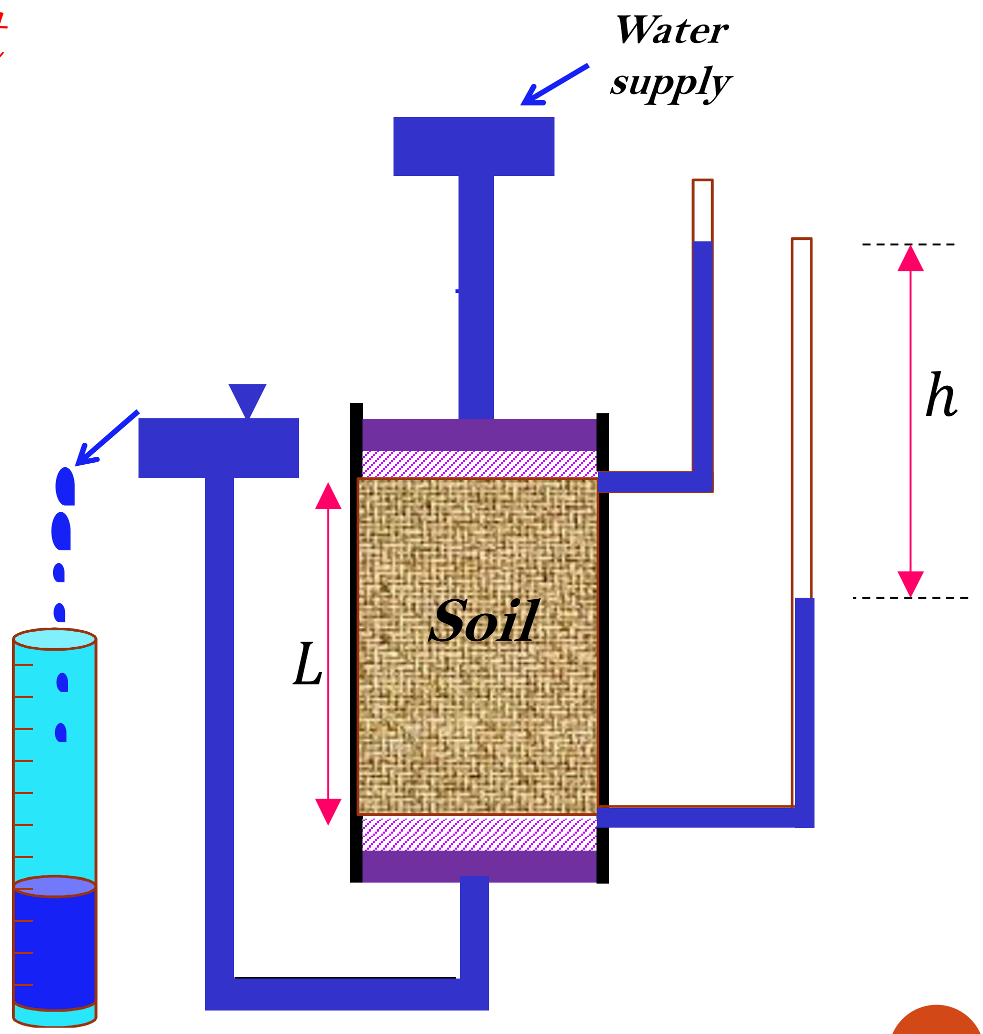
Constant – Head Test

The total volume of water collected may be expressed as:

$$Q = Avt = A(k \times i)t$$

or

$$K = \frac{QL}{Aht} \qquad (6-9)$$



Determination of Coefficient of Permeability

Constant – Head Test

Where :

Q = *volume of water collected*

A = *area of cross section of the soil specimen*

t = *duration of water collection,*

and

$$i = \frac{\Delta h}{L}$$

Determination of Coefficient of Permeability

Falling – Head Test

- *Relatively for less permeable soils*
- *Water flows through the sample from a standpipe attached to the top of the cylinder.*
- *The head of water (h) changes with time as flow occurs through the soil. At different times the head of water is recorded.*

Determination of Coefficient of Permeability

Falling – Head Test

A typical arrangement of the falling-head permeability test is shown in figure in the next slid.

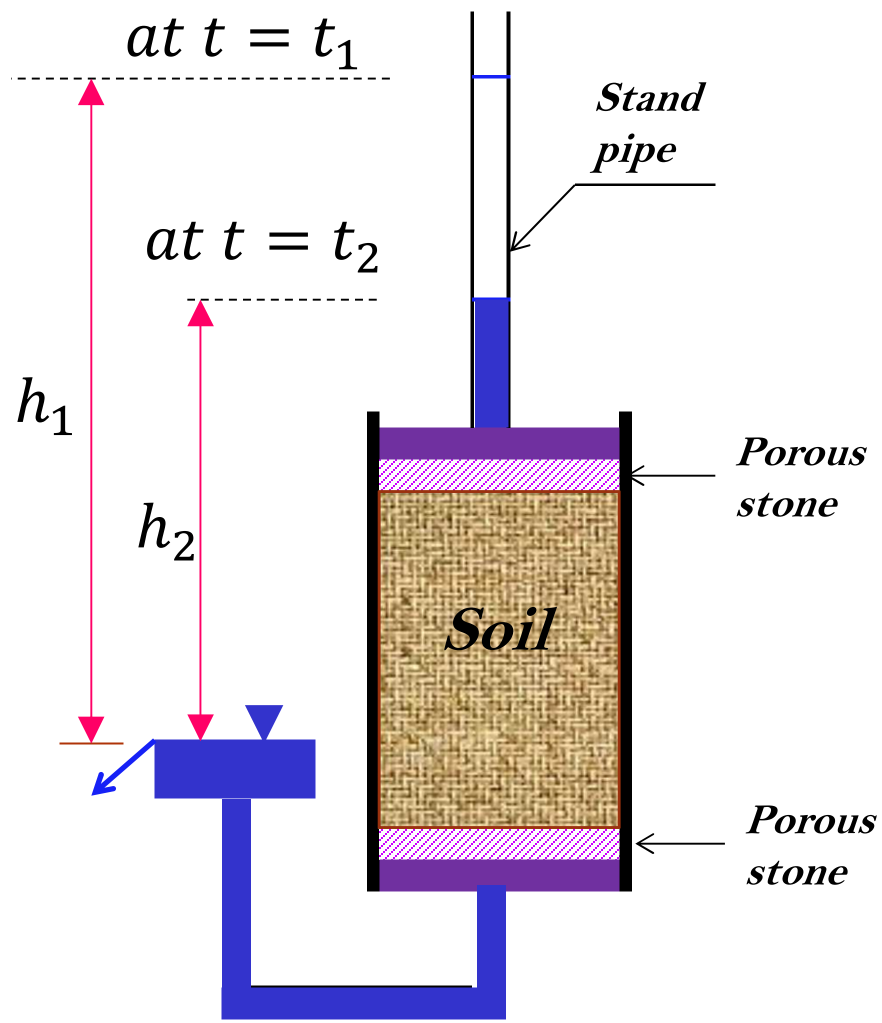
Water from a standpipe flows through the soil , the initial head difference $h1$ at time $t=0$ is recorded and water is allowed to flow through the soil specimen such that the final head difference at time $t = t2$ is $h2$.

Determination of Coefficient of Permeability

Falling – Head Test

For the falling-head test, the velocity of fall in the standpipe is:

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



Determination of Coefficient of Permeability

Falling – Head Test

The flow into the sample is: $q_{in} = -a \frac{dh}{dt}$

a= area of standpipe

From Darcy's law the flow out is

$$q_{out} = k \frac{h}{L} A$$

$$q_{out} = q_{int}$$

or

$$k \frac{h}{L} A = -a \frac{dh}{dt}$$

Determination of Coefficient of Permeability

Falling – Head Test

Separating variables and integrating over the limits:

$$k \frac{A}{L} \int_{T_1}^{T_2} dt = a \int_{h_2}^{h_1} \frac{dh}{h}$$

We obtain

t = time

L = Length of the fine soil

A = cross section area of soil

a= cross section area of tube

K = Coefficient of permeability

$$k = \frac{a L}{A \Delta t} \ln \frac{h_1}{h_2}$$

$$k = \frac{2.303\, a L}{A\ t} \log \frac{h_1}{h_2} \qquad (6-10)$$

Determination of Coefficient of Permeability

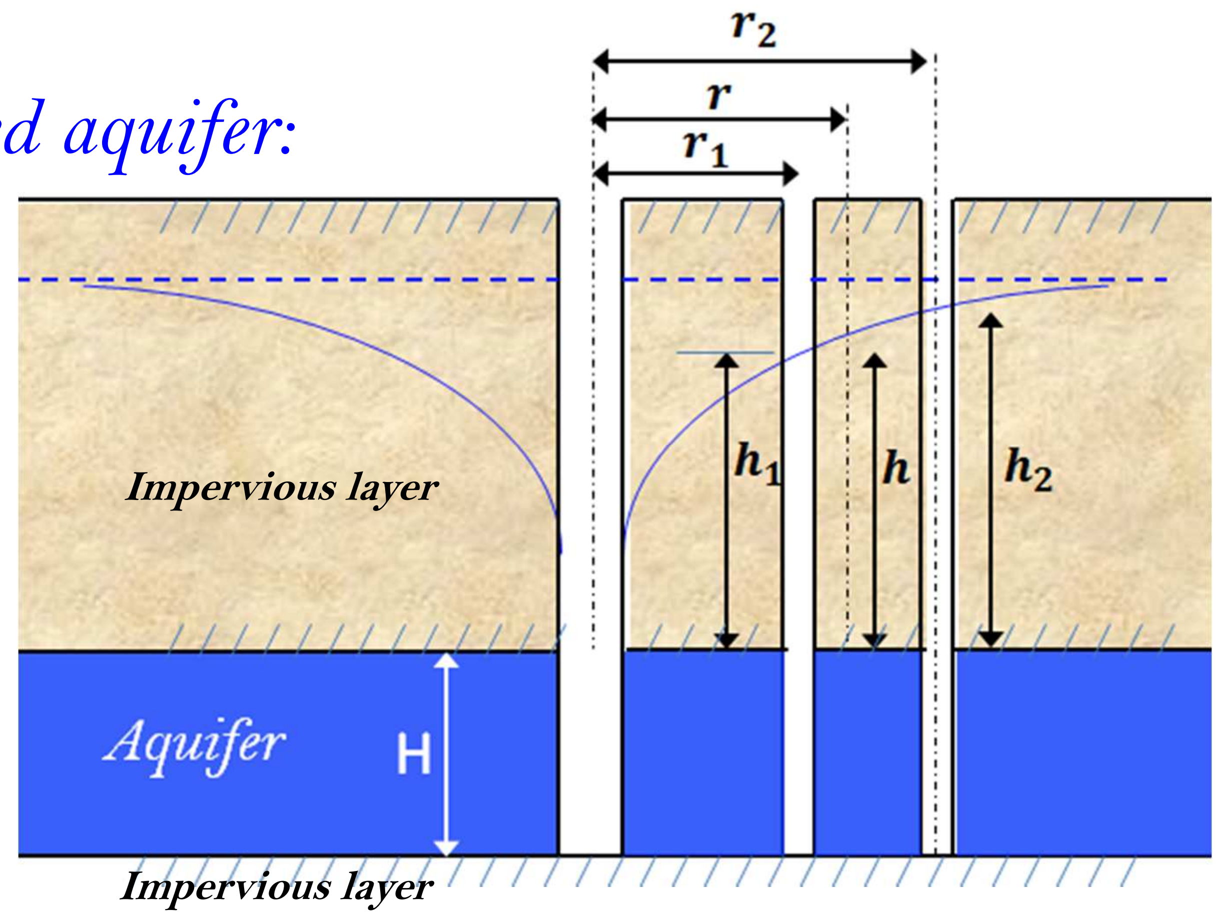
Field Tests for K

Field tests are generally more reliable than laboratory tests for determining soil permeability , the main reason being that field tests are performed on the undisturbed soil exactly as it occurs in situ at the test location.

Field Tests for K

Pumping Method

- *Confined aquifer:*



Field Tests for K

Pumping Method

$$q = k\,i\,A = k\,\frac{dh}{dr}\,2\pi\,rH$$

$$\int_{r_1}^{r_2} q\,\frac{dr}{r} = \int_{h_1}^{h_2} 2\pi\,k\,H\,dh$$

Integrating gives

$$q\,\ln\frac{r_2}{r_1} = 2\pi kH\,(h_2 - h_1)$$

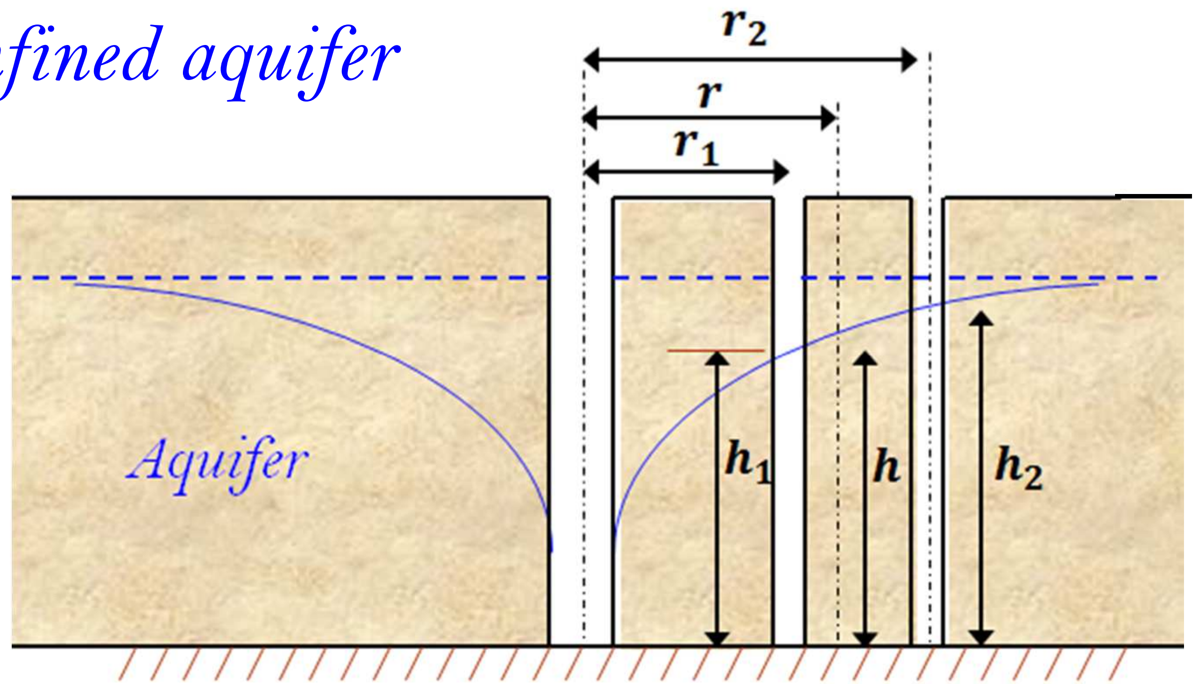
Solving for k yields

$$k = \frac{q\,\ln(r_2 / r_1)}{2\pi\,H\,(h_2 - h_1)} \qquad (6-11)$$

Field Tests for K

Pumping Method

- *Unconfined aquifer*



$$q = k\,i\,A = k\,\frac{dh}{dr}\,2\pi\,r\,h$$

Field Tests for K

Pumping Method

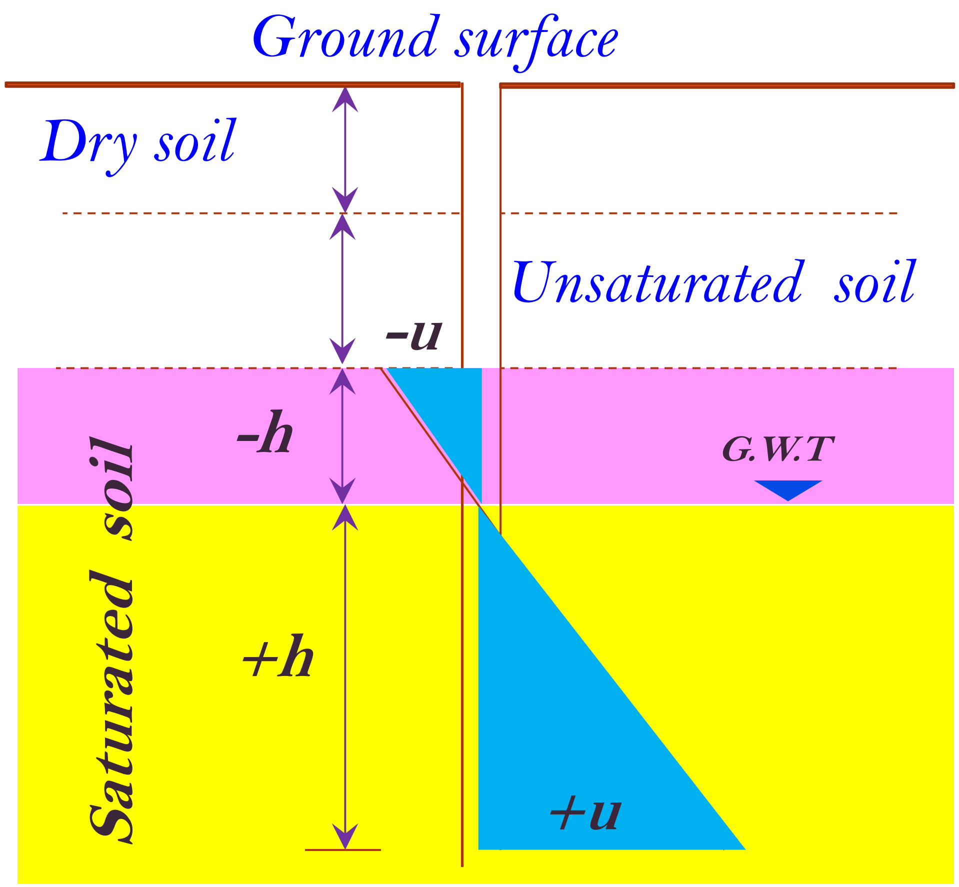
To determine k

$$\int_{r_1}^{r_2} q \frac{dr}{r} = \int_{h_1}^{h_2} 2\pi k h \, dh$$

$$q \ln \frac{r_2}{r_1} = \pi k \left(h_2^2 - h_1^2\right)$$

$$k = \frac{q \ln (r_2 / r_1)}{\pi (h_2^2 - h_1^2)} \qquad (6-12)$$

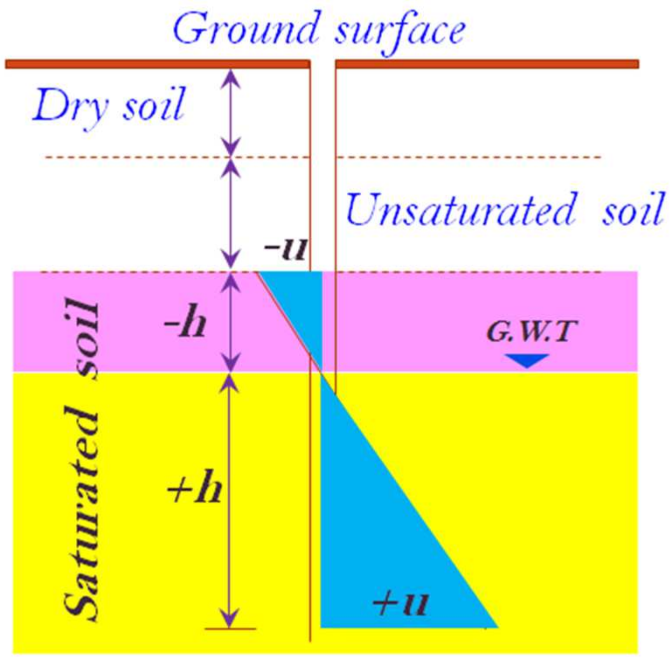
Capillary Rise in Soil



Capillary Rise in Soil

Above the water table, when the soil is saturated, pore pressure will be negative (less than atmospheric).

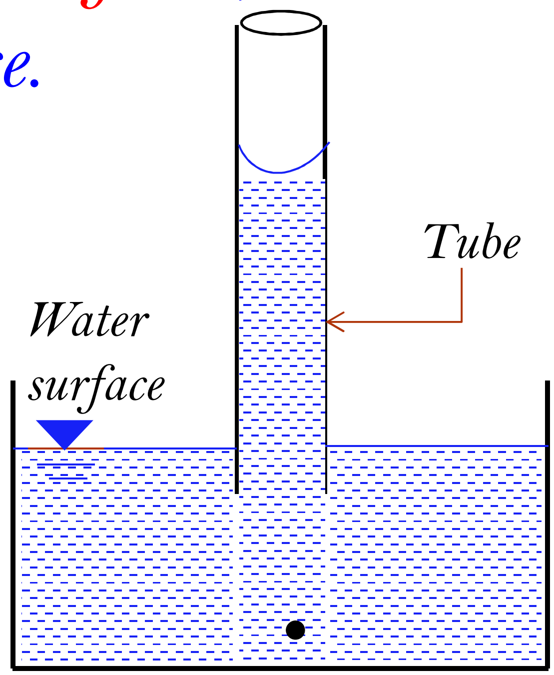
The height above the water table to which the soil is saturated is called the capillary rise, and this depends on the grain size and the size of pores. In coarse soils, the capillary rise is very small.



Capillary Rise in Soil

The continuous void spaces in soil can behave as bundles of capillary tubes of variable cross section.

Because of surface tension force, water may rise above the phreatic surface.

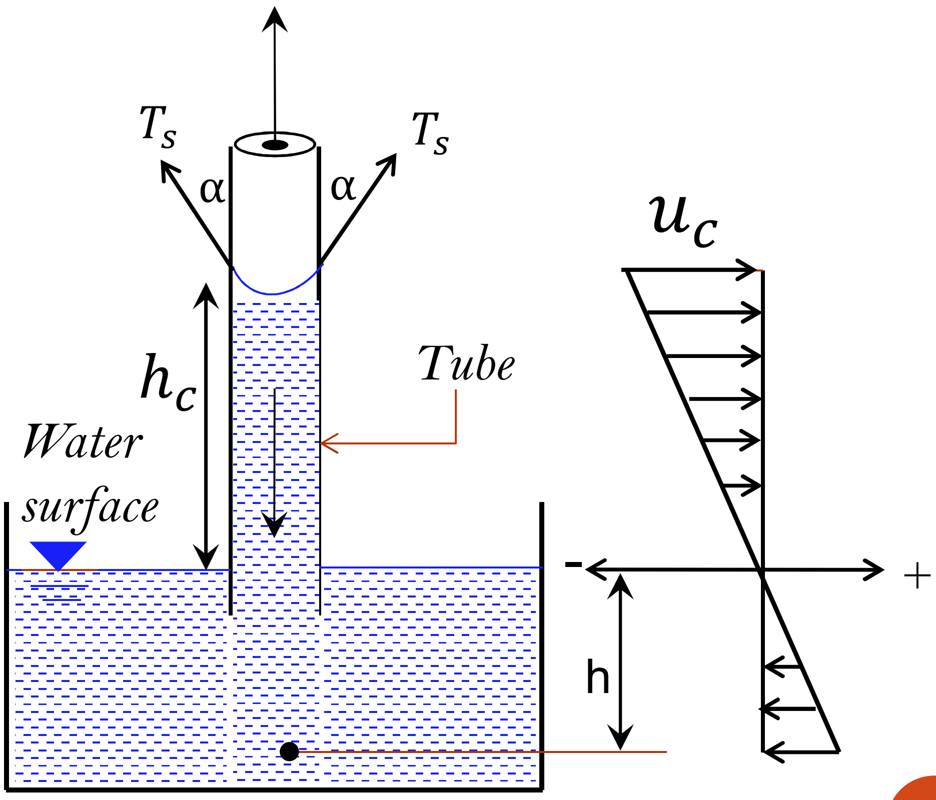


Capillary Rise in Soil

The height of rise of water in the capillary tube can be given by summing the forces in the vertical direction, or

$$\pi d\, T_s \cos\alpha = \frac{\pi d^2 h_c \gamma_w}{4}$$

$$h_c = \frac{4\; T_s \cos\alpha}{d \gamma_w} \qquad (6-13)$$



Capillary Rise in Soil

The surface tension T_s *of water at* $20^{\circ}C$ *can be taken as equal to* 75×10^{-8} *kN per cm. Equation (6- 13) can be simplified by assuming* $\alpha = 0$ *and by substituting for Ts. Therefore, for the case of water, the capillary height hc can be written as*

$$h_c = \frac{4\ T_s}{d\gamma_w} = \frac{4 * 75 \times 10^{-8} \times 10^{6}}{9.81\ d}$$

$$or\ \ h_c = \frac{0.3}{d} \qquad (6-14)$$

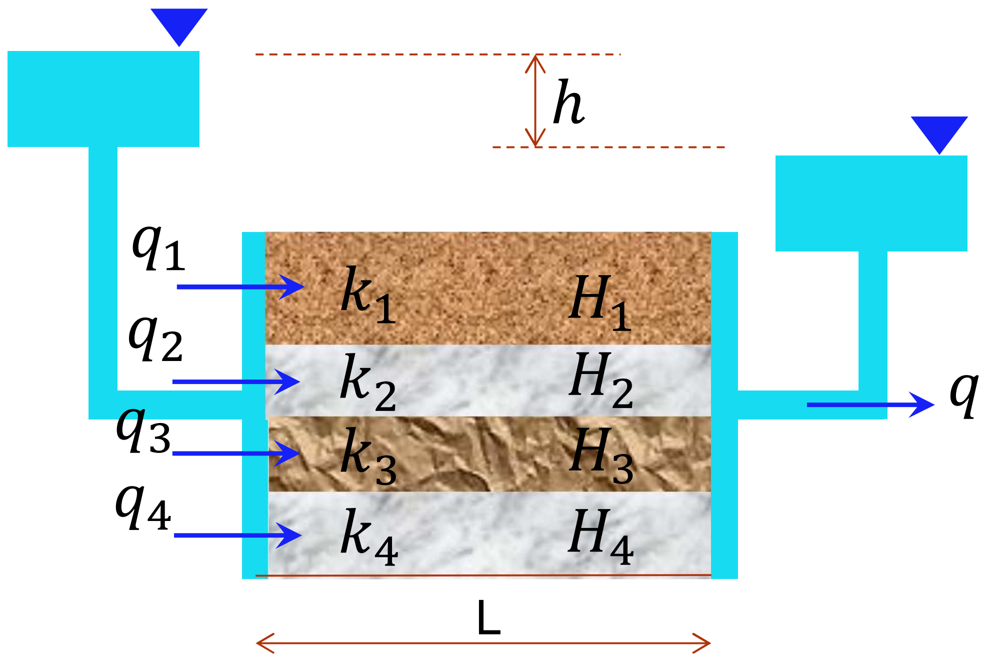
hc and d are expressed in cm

Permeability in Stratified Soil

In general, natural soil deposits are stratified In a stratified soil deposit where the hydraulic conductivity for flow in a given direction changes from layer to layer, an equivalent hydraulic conductivity can be computed to simplify calculations.

Permeability in Stratified Soil

Flow in the horizontal direction (parallel to layer



Permeability in Stratified Soil

Flow in the horizontal direction (parallel to layer)

The total flow through the cross section in unit time can be written as:

$$q = q_1 + q_2 + q_3 + \cdots + q_n$$

$$v \times 1 \times H = v_1 \times 1 \times H_1 + v_2 \times 1 \times H_2 + \cdots + v_n \times H_n$$

where

v = *average discharge velocity*

v_1 , v_2, v_3, … v_n = *discharge velocities of flow in layers*

Permeability in Stratified Soil

Flow in the horizontal direction (parallel to layer

For horizontal flow, the head h over the same flow path length L will be the same for each layer.

So $i = i_1 = i_2 = \cdots = i_n$

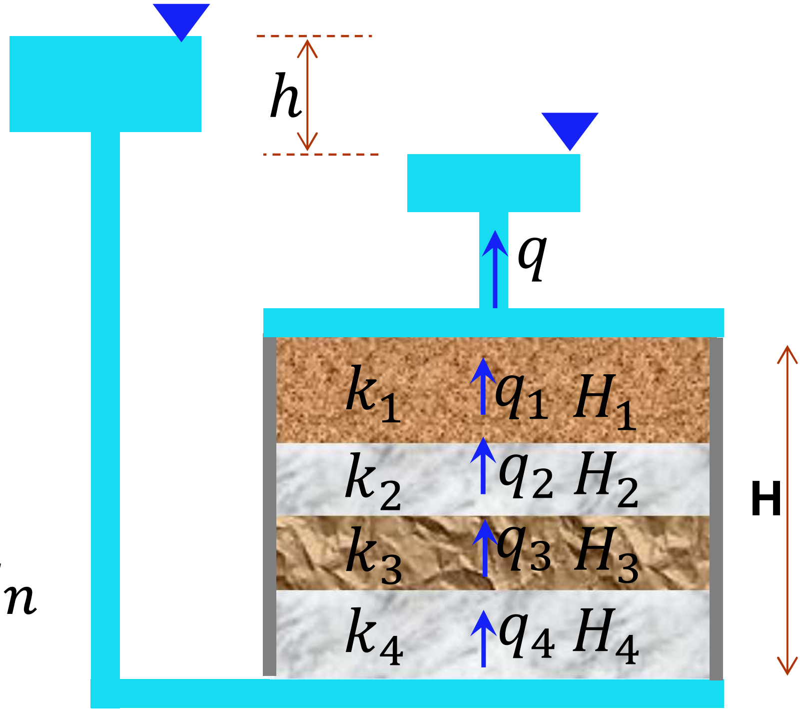
An equivalent coefficient of permeability in horizontal direction is:

$$k_H = \frac{1}{H}(k_{H1} \times H_1 + k_{H2} \times H_2 + \ldots.. + k_{Hn} \times H_n) \quad (6-14)$$

Permeability in Stratified Soil

Flow in the vertical direction (perpendicular to layers)

For vertical flow, the flow rate, q through area A of each layer is the same.



$$q = q_1 = q_2 = \cdots = q_n$$

Permeability in Stratified Soil

Flow in the vertical direction (perpendicular to layers)

The total head loss is the sum of head losses in all layers

$$h = h_1 + h_2 + h_3 + \ldots\ldots + h_n$$

$$iH = i_1 H_1 + i_2 H_2 + i_3 H_3 + \ldots\ldots + i_n H_n$$

$$v = v_1 = v_2 = v_3 = \ldots\ldots = v_n$$

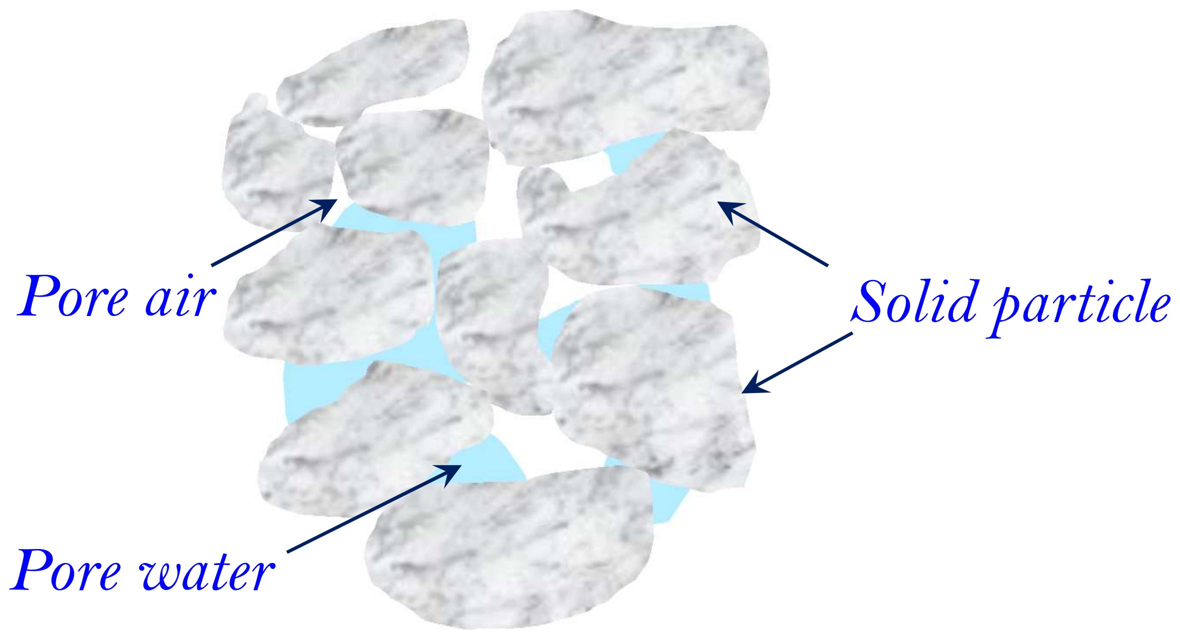
Permeability in Stratified Soil

Flow in the vertical direction (perpendicular to layers)

An equivalent (average) coefficient of permeability in vertical direction is

$$k_v = \frac{H}{\left(\frac{H_1}{k_1}\right) + \left(\frac{H_2}{k_2}\right) + \left(\frac{H_3}{k_3}\right) + \ldots\ldots\ldots + \left(\frac{H_n}{k_n}\right)} \qquad (6-15)$$

In stratified soils, average horizontal permeability is greater than average vertical permeability .


Pore air
Solid particle
Pore water

Worked Examples

Example 1

Refer to the constant –head arrangement shown in figure (slide No 22). For a test, the following are given:

a) L = 400 mm
b) A = 135 cm^2
c) h = 450 mm
d) Water collected in 3 min = 640 cm^3
e) Void ratio of soil = 0.54

Determine the

1) Coefficient of permeability
2) Seepage velocity

Worked Examples

Example 2

In a constant – head permeability test in the laboratory, the following are given:

L = 300 mm and A = 110 cm^2.

If the value of k = 0.02 cm/sec and a flow rate of 140 cm^3/min must be maintained through the soil, what is the head difference, h, across the specimen? Also, determine the discharge velocity under the test conditions.

Worked Examples

Example 3

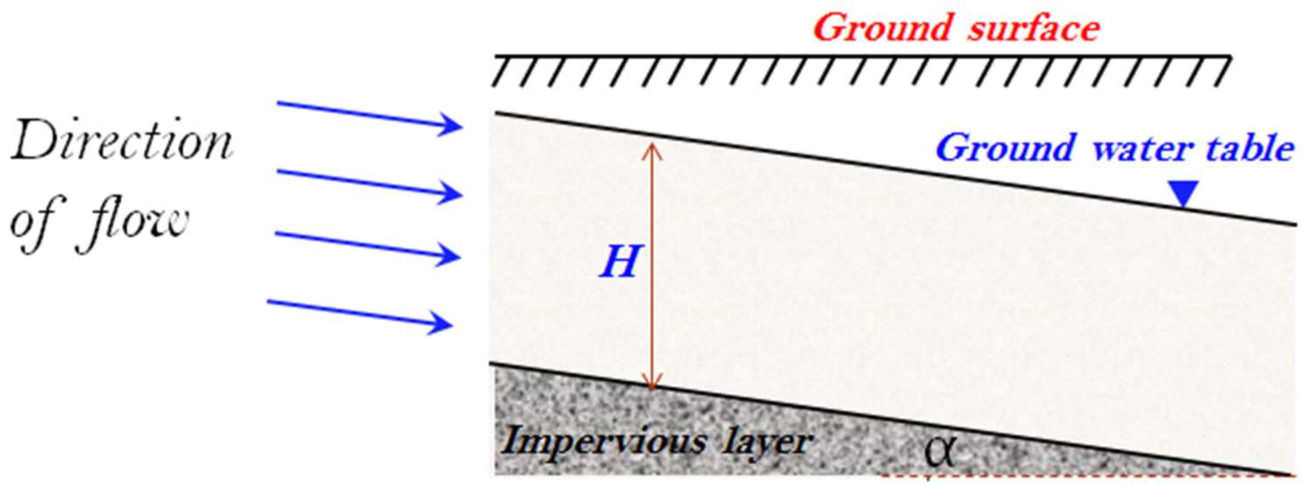
For a variable – head test, the following are given: length of specimen = 380 mm; area of specimen = 6.5 cm^2;

$k = 0.175$ cm/min. What should be the area of the standpipe for the head to drop from 650 cm to 300 cm in 8 min?

Worked Examples

Example 4

A permeable soil layer is underline by animpervious layer, as shown in figure. With k = 0.0048 cm/sec for the permeable layer, calculate the rate of seepage through it in m^3 /hr/m width if H= 3m and $\alpha = 5$

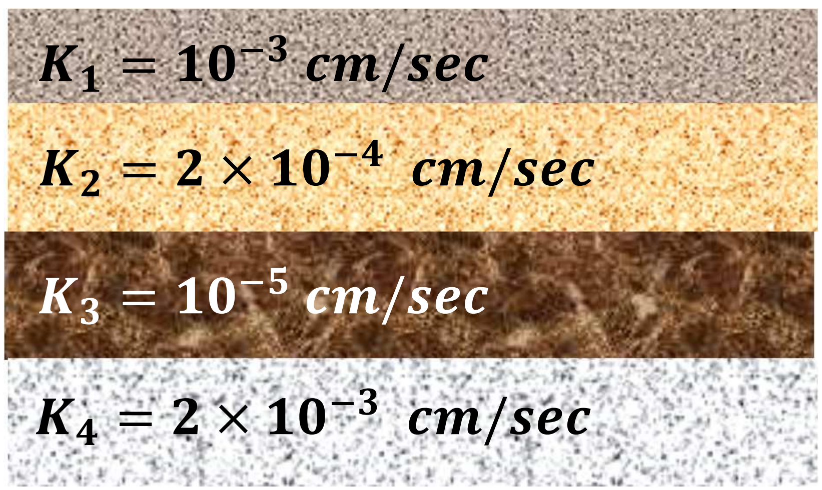


Worked Examples

Example 5

A layered soil is shown in figure below. Estimate the ratio of equivalent permeability

$$\frac{k_{h(eq)}}{k_{v(eq)}}$$



$H_1 = 1.5\ m$

$H_2 = 2\ m$

$H_3 = 4\ m$

$H_4 = 3\ m$

Not to scale