Chapter 4

Permeability

CHAPTER HIGHLIGHTS

- Introduction
- Hydraulic head (h)
- Darcy's law
- Seepage velocity (vs)
- Coefficient of absolute permeability (k_o)
- General expression for coefficient of permeability of soil
- Factors affecting permeability of soils
- Determination of coefficient of permeability

Introduction

This chapter outlines the concept of permeability of soil. The various methods used for determination of permeability of soil are also discussed. Several factors affecting permeability and, also a general expression for permeability of soils is explained. The expressions for permeability of soil in stratified soil deposits are also discussed.

- Important engineering property of soils.
- The property of soil which permits flow of water (or any other liquid) through it, is known as permeability.

Hydraulic Head (*h*)

- Total head at any point in a flowing fluid is equal to the elevation (or datum) head, the pressure head and the velocity head.
- Velocity head is neglected in case of water flowing through soils.
- The loss of head per unit length of flow through the soil is equal to the hydraulic gradient (i).

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

Where

h = Hydraulic head

L = Length of soil specimen

Darcy's Law

- Water flowing through soil is governed by Darcy's law.
- For laminar flow in a homogeneous soil, the velocity of flow (v) is given by:

$$\boxed{V = k \cdot i}$$

Where

k = Coefficient of permeability

i = Hydraulic gradient

v = Velocity of flow. It is also known as discharge velocity or superficial velocity.

- The discharge q is obtained by multiplying velocity of flow (V) by the total cross-sectional area of soil (A) normal to the direction of flow.

$$\boxed{q = V \cdot A = k \cdot i \cdot A}$$

NOTE

If the hydraulic gradient is unity, the coefficient of permeability is equal to velocity of flow.

- **Units:** mm/s, cm/s, m/day

The typical values of coefficient of permeability of different soils are given as follows:

Soil Type	Coefficient of Permeability (mm/s)	Drainage Properties
Clean gravel	10^{+1} to 10^{+2}	Very good
Coarse and medium sands	10^{-2} to 10^{+1}	Good
Fine sands, loose silt	10^{-4} to 10^{-2}	Fair
Dense silt, clayey silt	10^{-5} to 10^{-4}	Poor
Silty clay, clay	10^{-8} to 10^{-5}	Very poor

Validity of Darcy's law:

- Darcy's law is valid if the flow through soils is laminar.
- Flow will be laminar only if Reynolds number is less than unity.
- For flow through soils, the characteristic length in the Reynolds number is taken as average particle diameter.
- Darcy's law is valid for flow in clays, silts and fine sands.

Seepage Velocity (v_s)

$$V_s = \frac{V}{n}$$

Where

n = Porosity

V = Discharge velocity

$$V_s = \frac{k_i}{n}$$

$$V_s = k_P i$$

$$k_P: \text{Coefficient of percolation} = \frac{k}{n}$$

k_P is always greater than k.

Coefficient of Absolute Permeability (k_o)

It is independent of properties of water. It depends only on the characteristics of soil.

$$k_o = k\frac{\mu}{\gamma_w}$$

Units: mm^2, cm^2, m^2 or darcy.

$$1 \text{ darcy} = 0.987\times10^{-8} \text{ cm}^2$$

General Expression for Coefficient of Permeability of Soil

$$k = CD^2\left(\frac{\gamma_w}{\mu}\right)\left(\frac{e^3}{1+e}\right)$$

Where

D = Effective grain size = D_{10}

γ_w = Unit weight of percolating fluid

μ = Viscosity of percolating fluid

e = Void ratio

C = Shape constant depends upon type of soil, shape of soil particle and packing.

Factors Affecting Permeability of Soils

1. **Particle size:** k is proportional to the square of particle size (D).

$$k \propto D_{10}^2$$

2. **Shape of particles:** For the same void ratio, the soils with the angular particles are less permeable than those with rounded particles, as the permeability is inversely proportional to the specific surface.
3. **Void ratio:** k varies as $\frac{e^3}{1+e}$. But, the soils with the largest void ratio are the least pervious. This is due to the fact that the individual void passages in clays are extremely small through which water cannot flow.
4. **Properties of water**

$$k \propto \frac{\gamma_w}{\mu}$$

- Due to temperature variation, there is a large variation in the value of coefficient of viscosity (μ).
- The coefficient of permeability increases with an increase in temperature due to reduction in viscosity.
- As per IS:2720; the coefficient of permeability is to be reported at 27°C.
- If k is measured at other temperature, the following equation to be used:

$$k_{27} = k_t\frac{\mu_t}{\mu_{27}}$$

Where

k_{27} = Coefficient of permeability at 27°C when viscosity is μ_{27}.

k_t = Coefficient of permeability at t°C when viscosity is μ_t.

5. **Degree of saturation:** The permeability of a partially saturated soil is considerably smaller than that of a fully saturated soil due to pressure of air, which causes blockage of passage.
6. **Adsorbed water:** It reduces the permeability of soil as it causes an obstruction to flow of water in the pores.
7. **Impurities in water:** It reduces the permeability of soil.

Determination of Coefficient of Permeability

'k' can be determined by the following methods.

1. Laboratory methods:
   (a) Constant head permeability test
   (b) Variable head permeability test
2. Field methods:
   (a) Pumping out tests
   (b) Pumping in tests
3. Indirect methods
4. Capillary-permeability test.

Constant Head Permeability Test

- Test is conducted in an instrument known as constant head permeameter.
- This test is suitable for cleaning sand and gravel with $k > 10^{-2}$ mm/s.
- In this test, k is calculated by using the formula,

$$q = k \cdot i \cdot A$$

$$\boxed{k = \frac{q}{iA} = \frac{qL}{Ah}}$$

- The discharge 'q' is equal to the volume of water collected divided by time.

Variable-head Permeability Test

- This test is suitable for very fine sand and silt with $k = 10^{-2}$ to 10^{-5} mm/s.
- The instruments used are known as permeameters.
- In this test, k is calculated by using the formula,

$$\boxed{k = \frac{aL}{At}\log_e\frac{h_1}{h_2}}$$

Where
a = Area of stand pipe
A = Cross-sectional area of soil specimen
L = Length of soil specimen
t = Time interval in which head drops from h_1 to h_2.

SOLVED EXAMPLE

Example 1

In a falling head permeameter test on a silty clay sample, the following results were obtained; sample length 120 mm; sample diameter 80 mm; initial head 1200 mm, final head 400 mm; time for fall in head 6 minutes, stand pipe diameter 4 mm. Find the coefficient of permeability of soil in mm/s. **[GATE, 1998]**

Solution

Given:
Sample length, L = 120 mm, Diameter, D = 80 mm,

$A = \frac{\pi}{4}(80)^2 = 5026.54$ mm^2, h_1 = 1200 mm,

h_2 = 400 mm; t = 6 minutes = 6 × 60 second = 360 second.

a = Area of stand pipe = $\frac{\pi}{4}(4)^2 = 12.566$ mm^2

$$K = \frac{aL}{At}\log_e\left(\frac{h_1}{h_2}\right)$$
$$= \frac{12.566 \times 120}{5026.54 \times 360}\log_e\left(\frac{1200}{400}\right)$$

$k = 9.16 \times 10^{-4}$ mm/s
Hence, the answer is 9.16×10^{-4} mm/s.

Pumping Out Tests

- These are the most accurate tests.
- This test is conducted to measure permeability of soils for large engineering projects.
- In a pumping out test, soil deposit over a large area is influenced and represents an overall coefficient of permeability of a large mass of soil.
- Pumping out tests are expensive.
- For unconfined aquifer, the coefficient of permeability 'k' is given by:

$$\boxed{k = \frac{q}{\pi\left(Z_2^2 - Z_1^2\right)}\log_e\frac{r_2}{r_1}}$$

Where
Z_1 = Height of water level in observation well (1) at a radial distance of r_1.
Z_2 = Height of water level in observation well (2) at a radial distance of r_2.

- For confined aquifer, the coefficient of permeability is given by:

$$\boxed{k = \frac{q}{2\pi b(Z_2 - Z_1)}\log_e\frac{r_2}{r_1}}$$

b = Thickness of confined aquifer.

Pumping-in Tests

- This test is conducted to determine the coefficient of permeability of an individual stratum.
- There are two types of pumping-in tests:
  (a) Open-end test
  (b) Packer test.

$$\boxed{i = i_1 = i_2}$$

- In an open-end test, water flows out of the test hole through its bottom ends, whereas in packer test, water flows out through sides.
- Packer test are commonly used for testing of rocks.

Indirect Methods

1. **Allen Hazen's formula:**

$$k = CD_{10}^2$$

k = Coefficient of permeability (cm/s)
D_{10} = Effective size (cm)
C = A constant with a value between 100–150.

2 **Consolidation test data:** This method is suitable for very fine-grained soils (e.g., clays) with $k < 10^{-5}$ mm/s.

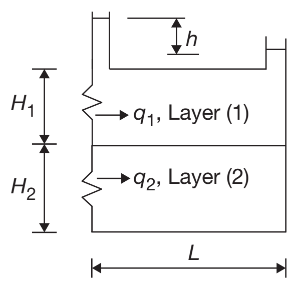
Capillary–permeability Test

- This is suitable for unsaturated or partially saturated soils.

Permeability of Stratified Soil Deposits

- **Stratified soil:** Soil consisting number of layers having different permeabilities.
  (a) Flow parallel to plane of stratification:
    - For flow parallel to plane of stratification, loss of head (h) over a length (L) is same for all layers.
    - Hydraulic gradient is same for all layers.
    - Total discharge (q) per unit width is equal to the sum of discharges in the individual layers.

$$\boxed{q = q_1 + q_2}$$

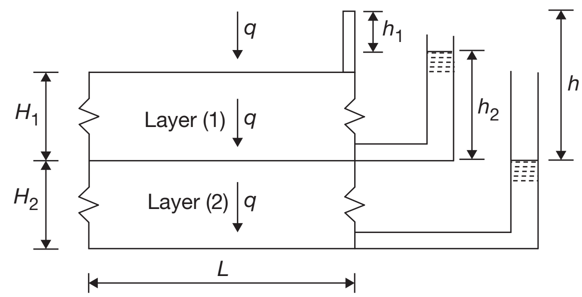


Overall coefficient of permeability,

$$\boxed{k_h = \frac{(k_h)_1 \times H_1 + (k_h)_2 \times H_2 + ...}{H_1 + H_2 + ...}}$$

(b) Flow normal to the plane of stratification:
- Discharge per unit width is the same for each layer.
- Total loss of head (h) or hydraulic gradient (i) over the entire deposit is equal to the sum of loss of heads or the sum of hydraulic gradients in the individual layer.

$$\boxed{\begin{matrix} q_1 = q_2 = q \\ h = h_1 = h_2 \end{matrix}}$$



Overall coefficient of permeability,

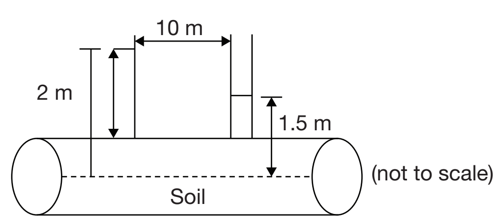
$$K_v = \frac{H_1 + H_2 + \cdots}{\dfrac{H_1}{(K_V)_1} + \dfrac{H_2}{(K_V)_2} + \cdots}$$

Exercises

1. A soil mass has coefficient of horizontal and vertical permeability as 9×10^{-7} cm/s and 4×10^{-7} cm/s, respectively. The transformed coefficient of permeability of an equivalent isotropic soil mass is
   (A) 9×10^{-7} cm/s. (B) 4×10^{-7} cm/s.
   (C) 13×10^{-7} cm/s. (D) 6×10^{-7} cm/s.

2. According to Darcy's law for flow through porous media, the velocity is proportional to
   (A) effective stress.
   (B) hydraulic gradient.
   (C) cohesion.
   (D) stability number.

3. Estimate the flow quantity (in liters per second) through the soil in the pipe is shown in the following figure. The pressure heads at two locations are shown in the figure. The internal diameter of the pipe is 1 m and the coefficient of permeability of the soil is 1×10^{-5} m/s.



4. In a falling head permeability test the initial head of 1.0 m dropped to 0.35 m in 3 hours, the diameter of the stand pipe being 5 mm. The soil specimen was 200 mm long and of 100 mm diameter. The coefficient of permeability of the soil is

(A) 4.86×10^{-5} cm/s
(B) 4.86×10^{-6} cm/s
(C) 4.86×10^{-7} cm/s
(D) 4.86×10^{-8} cm/s

5. In a constant head permeameter with cross-sectional area of 10 cm^2, when the flow was taking place under a hydraulic gradient of 0.5, the amount of water collected in 60 seconds is 600 cc. The permeability of the soil is
(A) 0.002 cm/s (B) 0.02 cm/s
(C) 0.2 cm/s (D) 2.0 cm/s

6. A soil has a discharge velocity of 6×10^{-7} m/s and a void ratio of 0.5. Its seepage velocity is
(A) 18×10^{-7} m/s (B) 12×10^{-7} m/s
(C) 6×10^{-7} m/s (D) 3×10^{-7} m/s

7. If during a permeability test on a soil sample with a falling head permeameter, equal time intervals are noted for drop of head from 'h_1' to 'h_2' and again from 'h_2' to 'h_1', then which one of the following relations would hold good?
(A) $h_3^2 = h_1 h_2$
(B) $h_1^2 = h_2 h_3$
(C) $h_2^2 = h_1 h_3$
(D) $(h_1 - h_2) = (h_2 - h_3)$

8. Consider the following statements:
I. Constant head permeameter is best suited for determination of coefficient of permeability of highly impermeable soils.
II. Coefficient of permeability of a soil mass decreases with increase in viscosity of the pore fluid.
III. Coefficient of permeability of soil mass increases with increase in temperature of the pore fluid.

Which of these statements are correct?
(A) I and II (B) I and III
(C) II and III (D) I, II and III

9. Consider the following statements:
I. Coarse sand is more than a million times permeable than a high plasticity clay.
II. The permeability depends on the nature of soil and not on properties of liquid flowing through soil.
III. If a sample of sand and a sample of clay have the same void ratio, both samples will exhibit the same permeability.
IV. Permeability of soil decreases as the effective stress acting on the soil increases.
Which of these statements are correct?
(A) I and II (B) I and III
(C) I and IV (D) II and III

10. A stratum of soil consists of three layers of equal thickness. The permeability of both the top and the bottom layers is 10^{-4} cm/s; and that of the middle layer is 10^{-3} cm/s; then the value of the horizontal coefficient of permeability for the entire composite of the soil layers is
(A) 2×10^{-4} cm/s
(B) 3×10^{-4} cm/s
(C) 4×10^{-4} cm/s
(D) 5×10^{-4} cm/s

11. In a falling head permeability test the initial head of 1.2 m dropped to 0.4 m in 4 hours, the diameter of the stand pipe being 5 mm. The soil specimen was 300 mm long and of 150 mm diameter. The coefficient of permeability of the soil is _______.
(A) 2.54×10^{-5} cm/s
(B) 2.54×10^{-6} cm/s
(C) 2.54×10^{-4} cm/s
(D) 2.54×10^{-7} cm/s

12. In a constant head permeameter with cross-sectional area of 10 cm^2, when the flow was taking place under a hydraulic gradient of 0.6 the amount of water collected in 60 seconds is 720 cc. The permeability of the soil is _______.
(A) 0.2 cm/s
(B) 0.02 cm/s
(C) 0.002 cm/s
(D) 2 cm/s

13. The coefficient of permeability increases when,
(A) viscosity of fluid increases.
(B) viscosity of fluid decreases.
(C) temperature condition decreases.
(D) None of these

14. In a constant head permeameter with cross-sectional area of 10 cm^2, when the flow was taking place under a hydraulic gradient of 0.7, the amount of water collected in 60 seconds is 480 cc. The permeability of the soil is _______.
(A) 2.4 cm/s
(B) 1.2 cm/s
(C) 0.6 cm/s
(D) 0.88 cm/s

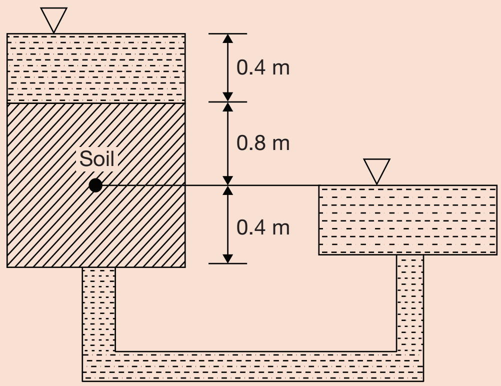
15. In a Darcian flow, flow velocity is _______.
(A) actual velocity
(B) seepage velocity
(C) discharge velocity
(D) boundary velocity

16. Two soil specimens with identical geometric dimensions were subjected to falling head permeability tests in the laboratory under identical conditions. The fall of water head was measured after an identical time interval. The ratio of initial to final water heads for the test involving the first specimen was 1.25. If the coefficient of permeability of the second specimen is 5 times that of the first, the ratio of initial to final water heads in the test involving the second specimen is _______.
(A) 3.05
(B) 3.80
(C) 4.00
(D) 6.25

Previous Years' Questions

Direction for questions 1 and 2:

Water is flowing through the permeability apparatus as shown in the figure. The coefficient of permeability of the soil is *k* m/s and the porosity of the soil sample is 0.50. **[GATE, 2007]**



1. The total head, elevation head and pressure head in meters of water at the point *R* shown in the figure are
   (A) 0.8, 0.4, 0.4
   (B) 1.2, 0.4, 0.8
   (C) 0.4, 0, 0.4
   (D) 1.6, 0.4, 1.2

2. What are the discharge velocity and seepage velocity through soil sample?
   (A) k, $2k$
   (B) $\frac{2}{3}k, \frac{4}{3}k$
   (C) $2k$, k
   (D) $\frac{4}{3}k, \frac{2}{3}k$

3. An open ended steel barrel of 1 m height and 1 m diameter is filled with saturated fine sand, having coefficient of permeability of 10^{-2} m/s. The barrel stands on a saturated bed gravel. The time required for the water level in the barrel to drop by 0.75 m is **[GATE, 2010]**
   (A) 58.9 s
   (B) 75 s
   (C) 100 s
   (D) 150 s

4. Two soil specimens with identical geometric dimensions were subjected to falling head permeability tests in the laboratory under identical conditions. The fall of water head was measured after an identical time interval. The ratio of initial to final water heads for the test involving the first specimen was 1.25. If the coefficient of permeability of the second specimen is 5 times that of the first, the ratio of initial to final water heads in the test involving the second specimen is **[GATE, 2012]**
   (A) 3.05
   (B) 3.80
   (C) 4.00
   (D) 6.25

5. Water is flowing at a steady rate through a homogenous and saturated horizontal soil strip of 10 m length. The strip is being subjected to a constant water head (*H*) of 5 m at the beginning and 1 m at the end. If the governing equation of flow in the soil strip is $\frac{d^2H}{dX^2} = 0$ (where *X* is the distance along the soil strip), the value of *H*(in m) at the middle of the strip is ________. **[GATE, 2014]**

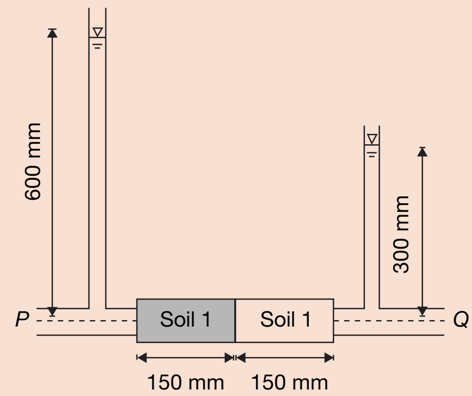
6. Which of the following statements is TRUE for the relation between discharge velocity and seepage velocity? **[GATE, 2015]**
   (A) Seepage velocity is always smaller than discharge velocity.
   (B) Seepage velocity can never be smaller than discharge velocity.
   (C) Seepage velocity is equal to the discharge velocity.
   (D) No relation between seepage velocity and discharge velocity can be established.

7. In an unconsolidated undrained tri-axial test, it is observed that an increase in cell pressure from 150 kPa to 250 kPa leads to a pore pressure increase of 80 kPa. It is further observed that, an increase of 50 kPa in deviatoric stress results in an increase of 25 kPa in the pore pressure. The value of Skempton's pore pressure parameter *B* is **[GATE, 2015]**
   (A) 0.5 (B) 0.625
   (C) 0.8 (D) 1.0

8. A non-homogeneous soil deposit consists of a silt layer sandwiched between a fine-sand layer at top and a clay layer below. Permeability of the silt layer is 10 times the permeability of the clay layer and one-tenth of the permeability of the sand layer. Thickness of the silt layer is 2 times the thickness of the sand layer and two-third of the thickness of the clay layer. The ratio of equivalent horizontal and equivalent vertical permeability of the deposit is __________. **[GATE, 2015]**

9. Water flows from *P* to *Q* through two soil samples, Soil 1 and Soil 2, having cross-sectional area of 80 cm2 as shown in the figure. Over a period of 15 minutes, 200 ml of water was observed to pass through any cross-section. The flow conditions can be assumed to be steady state. If the coefficient of permeability of Soil 1 is 0.02 mm/s, the coefficient of permeability of Soil 2 (expressed in mm/s) would be ________.

[GATE, 2016]



Answer Keys

Exercises

1. D	**2.** B	**3.** 3.92×10^{-4} lit/s	**4.** B	**5.** D	**6.** A	**7.** C	**8.** C	**9.** C
10. C	**11.** B	**12.** D	**13.** B	**14.** B	**15.** C	**16.** A		

Previous Years' Questions

1. A or C	**2.** A	**3.** B	**4.** A	**5.** 3	**6.** B	**7.** C	**8.** 10.96	**9.** 0.0454