Chapter 5

Effective Stress and Seepage Pressure

CHAPTER HIGHLIGHTS

- *Introduction*
- *Definitions*
- *Importance of effective stress*
- *Effect of water table fluctuations on effective stress*
- *Capillary water*
- *Frost heave*
- *Frost boil*
- *Seepage pressure (P_s)*
- *Quick Sand Condition*
- *Piping*
- *Prevention of piping failure*
- *Factor of safety against piping or quick sand*

Introduction

This chapter outlines the concept of effective stress in soils under hydrostatic conditions and, also for steady seepage conditions. The effect of seepage pressure on stability of soil masses are also described in this chapter.

Definitions

1. **Total stress:** Total stress at a point in soil mass is equal to the weight of soil (w) up to that point per unit area.

$$\sigma = \frac{w}{A} = \frac{\gamma_{sat} A \cdot h}{A}$$

$$\boxed{\sigma = \gamma_{sat} h}$$

[∵ Considering the soil sample as fully saturated.]

2. **Pore pressure (U):** Pore water pressure is the pressure due to the pore water filling the voids of the soil.

$$\boxed{U = \gamma_w h}$$

- It is also known as neutral pressure or neutral stress, because it cannot resist shear stress.

  Where

  γ_w = Unit weight of water

  h = Pressure head

3. **Effective stress ($\bar{\sigma}$):** The effective stress at a point in the soil mass is equal to the total stress minus the pore water pressure.

$$\boxed{\bar{\sigma} = \sigma - U}$$

- It is an abstract quantity, and it cannot be measured directly in the laboratory.
- It is equal to total normal force transmitted at points of contact divided by total area 'A', including that occupied by water.
- It has no physical meaning, and it is much smaller than the actual contact stress.

Importance of Effective Stress

- The engineering properties of a soil are controlled by the effective stress.
- The shear strength of a soil increases with increase in effective stress and settlement of a structure built on soils occurs due to increase in effective stress.

Effect of Water Table Fluctuations on Effective Stress

1. The effective stress at any section goes on increasing as the water table goes down. [Total stress and neutral pressure decreases.]

2. As the water table goes up, there is an increase in total stress and pore water pressure, but effective stress decreases.
3. The effective stress in a soil mass is independent of the depth of the water above the soil surface.
4. The effective stress depends upon the bulk unit weight above the water table and the submerged unit weight below the water table.
5. Due to the surcharge 'q', the increase in effective stress at each and every layer is same and is equal to 'q'.

Capillary Water

- The water held in the interstices of soils due to capillary forces is called 'capillary water'.
- In soils, the interconnected fine voids will act as a capillary tube.
- Capillary rise in small diameter tubes is given by:

Capillary rise, $$h_c = \frac{4T_s \cos\theta}{\gamma_w d}$$

Where

T_s = Surface tension

d = Diameter of the tube

θ = Angle of contact between the water and the wall of the tube.

If h_c and d both are in cm,

$$h_c = \frac{0.30}{d}$$

- As the capillary rise is inversely proportional to the diameter of the tube, the capillary rise is small in coarse-grained soils, but it may be very large in fine-grained soils.
- The height to which the capillary water rises in soils is known as capillary fringe.
- The water in capillary tube is under a negative pressure called 'tension'.
- The negative pressure causes an increase in the effective stress.

Frost Heave

- The water which migrates upward from the water table to capillary fringe may freeze, if the atmospheric temperature falls to the freezing point, and the ice is formed.
- This causes an increase in volume of soil and, thereby causes the lifting of light structures built on the ground.
- Soils which are prone to frost action are silts and fine sands.

Frost Boil

- The process of softening of soil due to increase in temperature is known as 'frost boil'.
- Soils most prone to the softening effect are silty soils. The clayey soils are not much affected as the silty soils.

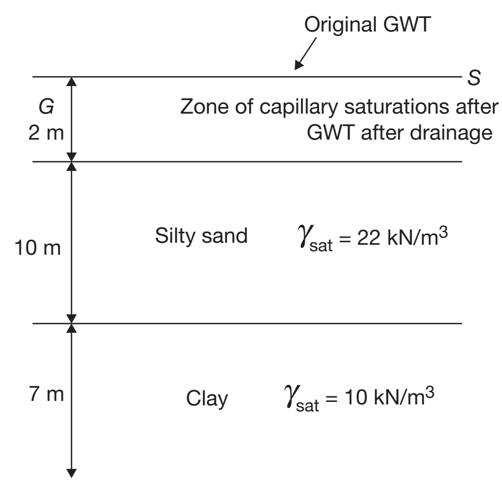
NOTE

The most effective method of prevention of frost action is to replace the frost-susceptible soils by coarse grained soils, or by providing insulation blanket between the water table and ground surface.

SOLVED EXAMPLES

Example 1

For the soils strata shown in the following figure, the water table is lowered by drainage by 2 m and, if the top 2 m thick silty sand stratum remains saturated by capillary action even after lowering of the water table, the increase in effective pressure in kPa at the middle height of the clay layer will be:



(A) 0.2 (B) 2
(C) 20 (D) 200

Solution

Case 1:

When WT is at ground surface.

At the middle height of the clay layer,

$$\sigma = (\gamma_{sat})Z_1 + (\gamma_{sat})Z_2$$
$$= (22)(12) + (19)(3.5)$$
$$\sigma = 330.5 \text{ kN/m}^2$$

Pore water pressure, $U = \gamma_w h_w$
$$= (9.81)(12 + 3.5)$$
$$U = 152.055 \text{ kN/m}^2$$

Effective stress, $\sigma' = \sigma - U$
$$= 330.5 - 152.055$$
$$\sigma' = 178.445 \text{ kN/m}^2$$ (A)

Case 2:
WT is lowered by 2 m and remains saturated by capillary action.

$$\sigma = (22)(12) + (19)(3.5)$$
$$\sigma = 330.5\ \text{kN/m}^2$$

Pore water pressure, $U = \gamma_w h_w$
$$= (9.81)(12 + 3.5 - 2)$$
$$U = 132.435\ \text{kN/m}^2$$

Effective stress, $\sigma' = \sigma - U$
$$= 330.5 - 132.435$$
$$\sigma' = 198.065\ \text{kN/m}^2$$

∵ The increase in effective pressure = 198.065 – 178.445 = 20 kN/m^2.

Seepage Pressure (P_s)

- The pressure induced in the soil due to the flow of water through a soil is known as seepage pressure.
- Seepage pressure (P_s) is given by,

$$\boxed{P_s = \gamma_w h}$$

- Seepage force (J) = $P_s \times A$

$$J = \gamma_w h \times A$$
$$J = \gamma_w i L \times A$$
$$\boxed{\frac{J}{A \times L} = \gamma_w \times i}$$

- Seepage force per unit volume is equal to the product of the hydraulic gradient (i) and the unit weight of water (γ_w).
- Seepage force always acts in the direction of flow.
- Seepage force affects the inter-particle forces and, hence the effective stress.
- The effective stress is increased when the flow is downward as the seepage force increases the inter-particle forces.
- When the flow is upward, the seepage force decreases the effective stress.

Quick Sand Condition

- Effective stress reduces to zero if the head causing upward flow is increased. This condition is known a quick sand condition.
- Quick sand is not a special type of soil. It is a hydraulic condition.
- It occurs in cohesionless soils only.
- Cohesive soil does not become quick as it still possess some strength equal to cohesion intercept.
- Quick condition is also known as boiling condition.
- This condition is most likely to occur in silt and fine sand.
- The hydraulic gradient at which effective stress becomes zero is known as critical hydraulic gradient (i_c).

$$\boxed{\begin{aligned} i_c &= \frac{\gamma'}{\gamma_w} \\ i_c &= \frac{(G-1)}{1+e} \end{aligned}}$$

- The critical hydraulic gradient at which a cohesionless soil becomes quick is about unity.
- Minimum head required to cause quick condition,

$$\boxed{h = \frac{\gamma' L}{\gamma_w}}$$

- Minimum head required to cause quick condition when there is surcharge,

$$\boxed{h = \frac{\gamma' L + q}{\gamma_w}}$$

Piping

Piping failure in the form of backward erosion or heave piping occurs when the seepage force, due to upward flow of water at any level, is greater than the submerged weight of soil above that level or when the exit gradient is greater than the critical hydraulic gradient.

- In case of backward erosion piping failure, the erosion of soil particles continues towards upstream side and a sort of pipe is formed.
- Failure by heave piping occurs in the form of a rise or a heave of large mass of soil due to seepage pressure.

Prevention of Piping Failure

1. Increasing the path of seepage:
    - By increasing the base width of hydraulic structure.
    - Providing vertical cut off walls below the hydraulic structure.
    - Providing an upstream impervious blanket.
2. Reducing seepage
3. Providing drainage filter: The drainage filter may be in the form of rock toe or chimney drain etc.
4. Loaded filter.

Example 2

For a saturated sand deposit, the void ratio and the specific gravity of solids are 0.70 and 2.67. The critical (upward) hydraulic gradient for the deposit would be:

(A) 0.54
(B) 0.98
(C) 1.02
(D) 1.87

Solution

Critical hydraulic gradient,

$$i_c = \frac{\gamma'}{\gamma_w}\frac{(G-1)}{1+e}$$

$$i_c = \frac{2.67-1}{1+0.70}$$

$$i_c = 0.98$$

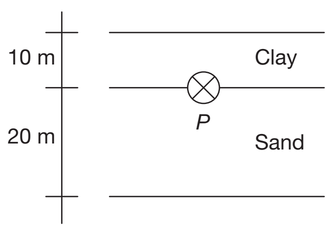
Factor of Safety Against Piping or Quick Sand

$$F = \frac{\text{Critical hydraulic gradient}}{\text{Actual or exit gradient}}$$

$$F = \frac{i_c}{i}$$

Exercises

1. A 10 m thick clay layer is underlain by a sand layer of 20 m depth (see the following figure). The water table is 5 m below the surface of clay layer. The soil above the water table is capillary saturated. The value of γ_{sat} is 19 kN/m^3. The unit weight of water is γ_w. If now the water table rises to the surface, the effective stress at a point P on the interface will

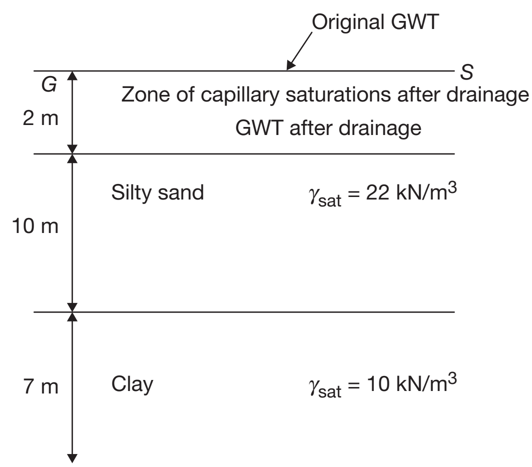


(A) increases by $5\gamma_w$.
(B) remain unchanged.
(C) decreases by $5\gamma_w$.
(D) decrease by $10\gamma_w$.

2. Which of the following statements is NOT true in the context of capillary pressure in soils?
(A) Water is under tension in capillary zone.
(B) Pure water pressure is negative in capillary zone.
(C) Effective stress increases due to capillary pressure.
(D) Capillary pressure is more in coarse grained soils.

3. A river 5 m deep consists of a sand bed with saturated unit weight of 20 kN/m^3, $\gamma_w = 9.81$ kN/m^3. The effective vertical stress at 5 m from the top of sand bed is
(A) 41 kN/m^2
(B) 51 kN/m^2
(C) 55 kN/m^2
(D) 53 kN/m^2

4. For the soil strata shown in the figure, the water table is lowered by drainage by 2 m and if the top 2 m thick silty sand stratum remains saturated by capillary action even after lowering of water table, the increase in effective vertical pressure in kPa at mid-height of clay layer will be

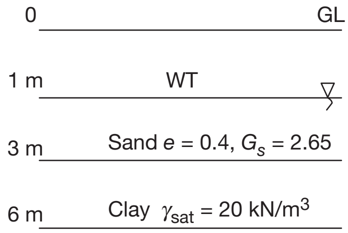


(A) 0.2
(B) 2
(C) 20
(D) 200

5. Assuming that a river bed level does not change and the depth of water in river was 10 m, 15 m and 8 m during months of February, July and December respectively of a particular year. The average bulk density of the soil is 20 kN/m^3. The bulk density of water is 10 kN/m^3. The effective stress at a depth of 10 m below the river bed during these months would be
(A) 300 kN/m^2 in February, 250 kN/m^2 in July and 320 kN/m^2 in December.
(B) 100 kN/m^2 in February, 100 kN/m^2 in July and 100 kN/m^2 in December.
(C) 200 kN/m^2 in February, 250 kN/m^2 in July and 180 kN/m^2 in December.
(D) 300 kN/m^2 in February, 350 kN/m^2 in July and 280 kN/m^2 in December.

6. For the subsoil condition shown in the figure calculate the total, neutral and effective stresses at 1 m, 3 m and 6 m elevations.

Assume $\gamma_w = 10$ kN/m^3



7. **Assertion (A):** At depth z below the surface of a submerged soil, water pressure is $\gamma_w z$ and it is the stress caused by the water which is called the 'neutral stress'.

Reason (R): The water pressure acts equally in all directions and transmits the same fully in grain to grain contact causing compression in the soil.

(A) Both A and R are true and R is the correct explanation of A.
(B) Both A and R are true but R is not a correct explanation of A.
(C) A is true but R is false.
(D) A is false but R is true.

8. The total, neutral and effective vertical stresses (in t/m^2) at a depth of 5 m below the surface of a fully saturated soil deposit with a saturated density of 2t/m^3 would, respectively, be

(A) 5, 5 and 10 (B) 5, 10 and 5
(C) 10, 5 and 10 (D) 10, 5 and 5

9. Consider the following statements:

I. Effective stress in a sand layer below a lake with standing water does not alter as the water level fluctuates.
II. Regarding water table below the ground surface, any rise in the water table causes equal changes in both pore pressure and effective stress.
III. Capillary saturation will cause the effective stress in increase.

Which of the above statements are correct?

(A) I, II and III (B) I and II only
(C) II and III only (D) I and III only

10. **Assertion (A):** Permanent lowering of ground water table results in settlement of foundations.

Reason (R): Increase in effective stress does not result in settlement of strata.

(A) Both A and R are true and R is the correct explanation of A.
(B) Both A and R are true but R is not a correct explanation of A.
(C) A is true but R is false.
(D) A is false but R is true.

11. A flownet is drawn to obtain

(A) seepage, coefficient of permeability and uplift pressure.
(B) coefficient of permeability, uplift pressure and exit gradient.
(C) exit gradient, uplift pressure and seepage quantity.
(D) exit gradient, seepage and coefficient of permeability.

12. **Assertion (A):** Quick sand is not a type of sand but it is a condition arising in a sand mass.

Reason (R): When the upward seepage pressure becomes equal to the pressure due to submerged weight of a soil, the effective pressure becomes zero.

(A) Both A and R are true and R is the correct explanation of A.
(B) Both A and R are true but R is not a correct explanation of A.
(C) A is true but R is false.
(D) A is false but R is true.

13. A sand deposit has a porosity of 1/3 and its specific gravity is 2.5. The critical hydraulic gradient to cause sand boiling in the stratum will be

(A) 1.5 (B) 1.25
(C) 1.0 (D) 0.75

14. Consider the following statements:

I. Quantity of seepage in each flow channel of a flow-net is dependent on upstream head.
II. Drop in head between adjacent equipotential lines of a flow-net is dependent on upstream head.
III. With increase in the length of a flow path, the corresponding exit gradient will decrease.

Which of these statements are correct?

(A) I, II and III (B) I and II only
(C) I and III only (D) II and III only

15. A layer of saturated clay 5 m thick is overlain by sand 4.0 m deep. The water table is 3 m below the top surface. The saturated unit weight of clay and sand are 18 kN/m^3 and 20 kN/m^3 respectively. Above the water table, the unit weight of sand is 17 kN/m^3. Calculate the effective pressure on a horizontal plane at a depth of 9 m below the ground surface. What will be the increase in the effective pressure at 9 m if the soil gets saturated by capillary, up to height of 1 m above the water table? $\gamma_w = 9.81$ kN/m^3.

16. The specific gravity and in situ void ratio of a soil deposit are 2.71 and 0.85 respectively. The value of the critical hydraulic gradient is

(A) 0.82 (B) 0.85
(C) 0.92 (D) 0.95

17. The range of void ratio between which quick sand condition occurs in cohesion less granular soil despot is

(A) 0.4 – 0.5 (B) 0.6 – 0.7
(C) 0.8 – 0.9 (D) 1.0 – 1.1

18. A 1.25 m layer of soil ($n = 0.35$, $G = 2.65$) is subjected to an upward seepage of head of 1.85 m. What depth of coarse sand would be required above the existing soil to provide a factor of safety of 2 against piping? Assume that coarse sand has the same porosity and specific gravity as the soil, and that there is negligible head loss in sand. (Take $\gamma_w = 9.81$ kN/m^3)

19. A masonry dam is founded an pervious sand having porosity equal to 45% and specific gravity of sand particles is 2.65. For a desired factor of safety of 3 against sand boiling, the maximum permissible upward gradient will be

(A) 0.225 (B) 0.302
(C) 1.0 (D) None of these

20. A unit volume of a mass of saturated soil is subjected to horizontal seepage. The saturated unit weight is 22 kN/m^3 and the hydraulic gradient is 0.3. The resultant body force on the soil mass is

(A) 1.98 kN (B) 6.6 kN
(C) 11.49 kN (D) 22.97 kN

21. To provide safety against piping failure, with a factor of safety of 5, what should be the maximum permissible exit gradient for soil with specific gravity of 2.5 and porosity of 0.35?

(A) 0.155 (B) 0.167
(C) 0.195 (D) 0.213

22. In a 8 m thick stratum of fine sand having submerged density of 11 kN/m^3, quick sand condition occurred at a depth of 5.2 m of excavation. What is the depth of lowering of ground water table required for making an excavation 6 m deep?

(Take γ_w as 10 kN/m^3)

(A) 1.76 m (B) 1.68 m
(C) 0.88 m (D) 0.74 m

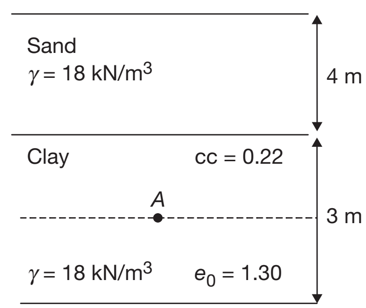
23. A soil has a discharge velocity of 12×10^{-7} m/s and a void ratio of 0.5. Its seepage velocity is

(A) 18×10^{-7} m/s
(B) 12×10^{-7} m/s
(C) 36×10^{-7} m/s
(D) 24×10^{-7} m/s

24. The stress which controls the strength and deformation behaviour of soil is _______.

(A) total pressure (B) pore pressure
(C) effective pressure (D) None of these

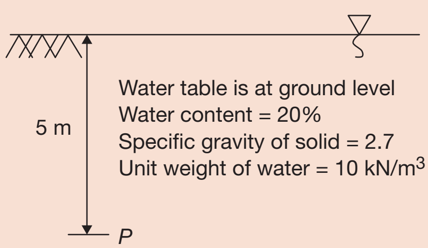
25. Calculate the final settlement of clay layer shown in the figure due to an increase of pressure of 30 kN/m^2 at mid-height of the layer. Take $\gamma_w = 10$ kN/m^3.



(A) 60.2 mm (B) 30.8 mm
(C) 19.6 mm (D) 82 mm

Previous Years' Questions

Direction for questions 1 and 2:
The ground conditions at a site are shown in the figure. **[GATE, 2008]**



1. The structural unit weight of sand (kN/m^3) is

(A) 15
(B) 18
(C) 21
(D) 24

2. The total stress, pore water pressure and effective stress (kN/m^2) at the point *P* are, respectively.

(A) 75, 50 and 25
(B) 90, 50 and 40
(C) 105, 50 and 55
(D) 120, 50 and 70

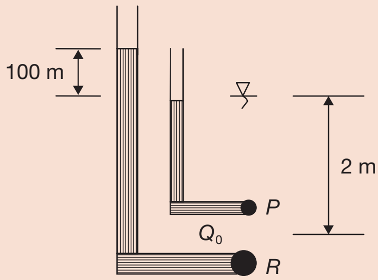
3. Quick sand condition occurs when **[GATE, 2010]**

(A) the void ratio of soil becomes 1.0.
(B) the upward seepage pressure in soil becomes zero.
(C) the upward seepage pressure in soil becomes equal to saturated unit weight of the soil.
(D) the upward seepage pressure in soil becomes equal to the submerged unit weight of the soil.

4. For a saturated sand deposit, the void ratio and the specific gravity of solids are 0.70 and 2.67, respectively. The critical (upward) hydraulic gradient for the deposit would be **[GATE, 2011]**

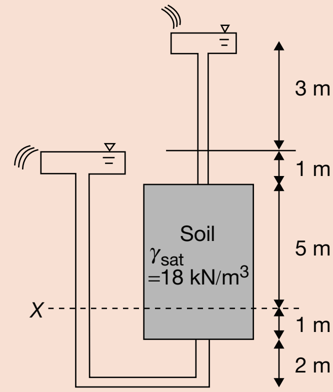
(A) 0.54 (B) 0.98
(C) 1.02 (D) 1.87

5. Steady state seepage is taking place through a soil element at *Q*, 2 m below the ground surface immediately downstream of the toe of an earthen dam as shown in the figure. The water level in a piezometer installed at *P*, 500 mm above *Q*, is at the ground surface. The water level in piezometer installed at *R*, 500 mm below *Q*, is 100 mm above the ground surface. The bulk saturated unit weight of the soil is 10 kN/m^3 and the unit weight of water is 9.81 kN/m^3. The vertical effective stress (in kPa) at *Q* is **[GATE, 2012]**



(A) 14.42
(B) 15.89
(C) 16.38
(D) 18.34

6. A seepage flow condition is shown in the figure. The saturated unit weight of the soil γ_{sat} = 18 kN/m^3. Using unit weight of water, γ_w = 9.81 kN/m^3, the effective vertical stress (expressed in kN/m^2) on plane *X-X* is ________. **[GATE, 2016]**



Answer Keys

Exercises

1. C **2.** D **3.** B **4.** C **5.** B **6.** – 18.92 kN/m^2, 42.48 kN/m^2, 72.51 kN/m^2 **7.** C
8. D **9.** D **10.** C **11.** C **12.** A **13.** C **14.** C **15.** 102.14 kN/m^2, 3 kN/m^2
16. C **17.** B **18.** 2.25 m **19.** B **20.** 12.37 kN **21.** C **22.** B **23.** C
24. C **25.** B

Previous Years' Questions

1. C **2.** C **3.** D **4.** B **5.** B **6.** 65.47