

CIVIL ENGINEERING

Soil Mechanics and Foundation Engineering



Comprehensive Theory
with Solved Examples and Practice Questions



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Soil Mechanics and Foundation Engineering

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CONTENTS

Soil Mechanics and Foundation Engineering

CHAPTER 1

Origin of Soil and its Formation 1-8

- 1.1 Introduction 1
- 1.2 Origin of Soil..... 1
- 1.3 Soil Deposits in India..... 4
- 1.4 Organic and Inorganic Soils..... 5
- 1.5 Common Types of Soils 6
- Objective Brain Teasers*..... 7

CHAPTER 2

Properties of Soils 9-88

- 2.1 Introduction 9
- 2.2 Phase Diagram..... 9
- 2.3 Basic Definitions..... 10
- 2.4 Some Important Relationships..... 15
- 2.5 Methods for Determination of Water Content..... 30
- 2.6 Determination of Specific Gravity of Soil Solids..... 33
- 2.7 Determination of In-Situ Unit Weight 35
- 2.8 Index Properties of Soils..... 39
- 2.9 Grain Size Analysis..... 40
- 2.10 Consistency of Clays (Atterberg's Limits) 50
- 2.11 Relative Density (ID or Dr) 67
- 2.12 Sensitivity (St) 72
- 2.13 Thixotropy 72
- 2.14 Activity (AC) 73
- 2.15 Collapsibility..... 74
- 2.16 Relationship between Atterberg Limits and
Engineering Properties..... 75
- Objective Brain Teasers*..... 79
- Conventional Brain Teasers*..... 86

CHAPTER 3

Identification & Classification of Soils...89-104

- 3.1 Introduction89
- 3.2 Field Identification of Soils89
- 3.3 Engineering Classification of Soils.....90
- 3.4 Classification of Coarse Grained Soil93
- 3.5 Classification of Fine Grained Soil.....97
- Objective Brain Teasers*..... 101

CHAPTER 4

Soil Structure and Clay Minerals 105-112

- 4.1 Introduction 105
- 4.2 Soil Structure..... 105
- 4.3 Clay Minerals 105
- 4.4 Structure of Clay Minerals 106
- 4.5 Isomorphous Substitution 107
- 4.6 Types of Clay Minerals 107
- 4.7 Clay Water Relationship..... 108
- 4.8 Clay Particle Interaction 109
- 4.9 Soil Structure..... 110
- 4.10 Types of Soil Structures 110
- Objective Brain Teasers*..... 112

CHAPTER 5

Soil Compaction 113-140

- 5.1 Introduction 113
- 5.2 Principles of Compaction 113
- 5.3 Difference between Compaction and
Consolidation..... 114
- 5.4 Advantages of Compaction 114

5.5	Laboratory Compaction.....	114
5.6	Comparison of Standard & Modified Proctor Test	116
5.7	Zero Air Void Line	118
5.8	Constant Percentage Air Void Lines.....	119
5.9	Factors Affecting Compaction	123
5.10	Compaction Behaviour of Sand	125
5.11	Effect of Compaction on Properties of Soils	125
5.12	Field Compaction and Equipment	128
5.13	Evaluation of Compaction.....	128
5.14	Compaction Quality Control	128
5.15	Settlement During Compaction.....	130
	<i>Objective Brain Teasers</i>	133
	<i>Conventional Brain Teasers</i>	137

CHAPTER 6

Principle of Effective Stress, Capillarity and Permeability..... 141-202

6.1	Introduction	141
6.2	Total Stress, Pore Pressure and Effective Stress.....	141
6.3	Physical Significance of Effective Stresses	143
6.4	Effective Stress in Partially Saturated Soils	145
6.5	Capillarity in Soils	145
6.6	Geostatic Stresses in Soils.....	151
6.7	Effect of Water Table Fluctuations on Effective Stress..	161
6.8	Permeability of Soils	164
6.9	Determination of Coefficient of Permeability	168
6.10	Factors Affecting Permeability.....	184
6.11	Coefficient of Absolute Permeability.....	186
6.12	Permeability of Stratified Soils.....	187
	<i>Objective Brain Teasers</i>	192
	<i>Conventional Brain Teasers</i>	200

CHAPTER 7

Seepage Through Soils..... 203-242

7.1	Introduction	203
7.2	Types of Head	203

7.3	Total Head	204
7.4	Seepage Pressure	204
7.5	Analysis of Seepage Force on Effective Stress	205
7.6	Quick Sand Condition	212
7.7	Laplace Equations	220
7.8	Flow Nets	220
7.9	Application of Flow Nets.....	221
7.10	Flow Through Non-Homogeneous Section	226
7.11	Piping Failure and its Protection	226
7.12	Seepage Through Earthen Dams.....	227
	<i>Objective Brain Teasers</i>	234
	<i>Conventional Brain Teasers</i>	238

CHAPTER 8

Stress Distribution in Soils243-270

8.1	Introduction	243
8.2	Boussinesq's Theory.....	243
8.3	Vertical Stress Distribution Diagrams.....	246
8.4	Westergaard's Theory	248
8.5	Comparison between Boussinesq and Westergaard Theories	250
8.6	Vertical Stresses beneath the loaded areas	251
8.7	Approximate Methods for Vertical Stress Computation	261
	<i>Objective Brain Teasers</i>	267
	<i>Conventional Brain Teasers</i>	268

CHAPTER 9

Compressibility and Consolidation of Soil271-330

9.1	Introduction	271
9.2	Compressibility.....	271
9.3	Initial Settlement	272
9.4	Consolidation.....	272
9.5	Normally and Over Consolidated Soils	273
9.6	Compression Test.....	274

9.7	Determination of Compressibility Parameters	278
9.8	Preconsolidation Pressure	281
9.9	Field Consolidation Curve	282
9.10	Graph between Void Ratio and Effective Stress	283
9.11	Time Rate of Consolidation [Mechanics of..... Consolidation]	284
9.12	Terzaghi's Theory of One Dimensional Consolidation....	285
9.13	Compression Ratios	289
9.14	Settlement Analysis	290
9.15	Vertical Sand Drains.....	315
	<i>Objective Brain Teasers</i>	316
	<i>Conventional Brain Teasers</i>	322

CHAPTER 10

Shear Strength of Soils.....331-382

10.1	Introduction	331
10.2	Shear Strength of Soil	331
10.3	Mohr failure criterion	334
10.4	Factors Affecting Shear Strength.....	339
10.5	Measurement of Shear Strength.....	340
10.6	Direct Shear Test	340
10.7	Triaxial Test.....	344
10.8	Unconfined Compression Test.....	360
10.9	Vane Shear Test	363
10.10	Pore Pressure Parameters	365
10.11	Stress Path.....	367
10.12	Liquefaction of Soil.....	368
	<i>Objective Brain Teasers</i>	369
	<i>Conventional Brain Teasers</i>	374

CHAPTER 11

Earth Pressure and Retaining Walls 383-466

11.1	Introduction	383
11.2	Retaining Structures.....	383
11.3	Types of Lateral Earth Pressure.....	385
11.4	Earth Pressure at Rest	386

11.5	Active and Passive Earth Pressure	389
11.6	Rankine's Theory:.....	391
11.7	Various Cases of Earth Pressure in Cohesionless Soil.....	393
11.8	Active and Passive Earth Pressure in Cohesive Soils.....	418
11.9	Coulomb's Wedge Theory.....	430
11.10	Sheet Pile Walls.....	432
11.11	Anchored Bulkhead.....	438
	<i>Objective Brain Teasers</i>	443
	<i>Conventional Brain Teasers</i>	447

CHAPTER 12

Stability of Slopes.....457-480

12.1	Introduction	457
12.2	Types of Slopes.....	457
12.3	Stability of Infinite Slopes.....	458
12.4	Definitions of Factor of Safety	464
12.5	Stability of Finite Slopes.....	466
12.6	Total Stress Analysis for a Purely Cohesive Soil.....	467
12.7	Swedish Method of Slices.....	469
12.8	Friction Circle Method	469
12.9	Effective Stress Analysis	471
12.10	Effective Stress Analysis by Bishop's Method	473
12.11	Taylor's Stability Number Method.....	473
	<i>Objective Brain Teasers</i>	475
	<i>Conventional Brain Teasers</i>	478

CHAPTER 13

Soil Exploration 481-494

13.1	Introduction	481
13.2	Purpose of Soil Exploration.....	481
13.3	Stage in Sub-surface Exploration	481
13.4	Methods of Exploration	482
13.5	Types of Soil Samples.....	486
13.6	Soil Samplers.....	487

13.7	Disturbance of Soil Samplers	489
13.8	Number and Disposition of Trial Pits and Borings..	492
	<i>Objective Brain Teasers</i>	492

CHAPTER 14

Soil Improvement..... 495-506

14.1	Introduction	495
14.2	Improvement Techniques	495
14.3	Reinforced Earth	498
14.4	Geotextiles : Definition and Types.....	501
14.5	Functions of Geotextiles	502
	<i>Objective Brain Teasers</i>	505

CHAPTER 15

Bearing Capacity and Shallow Foundation..... 507-564

15.1	Introduction	507
15.2	Types of Foundation.....	507
15.3	Selection of foundation	509
15.4	Bearing Capacity.....	511
15.5	Important Definitions	512
15.6	Mode of Shear Failure	513
15.7	Methods to Determine Bearing Capacity	515
15.8	Analytical Methods.....	515
15.9	Terzaghi's Method.....	518
15.10	Skempton's Method	534
15.11	Meyerhoff's Method	537

15.12	Plate load test	542
15.13	Standard Penetration Test	546
15.14	CONE PENETRATION Test.....	552
15.15	Settlement of Shallow Foundations	553
15.16	Heave of the Bottom of the Cut in Clay	554
	<i>Objective Brain Teasers</i>	555
	<i>Conventional Brain Teasers</i>	562

CHAPTER 16

Deep Foundation..... 565-615

16.1	Introduction	565
16.2	Floating Foundation.....	567
16.3	Classification of piles.....	567
16.4	Bearing capacity of pile.....	570
16.5	Static Method for ultimate bearing capacity of piles	572
16.6	Dynamic Method.....	578
16.7	Under-reamed Piles	581
16.8	Group Action of Piles	583
16.9	Negative skin friction.....	594
16.10	Design of Pile Group.....	597
16.11	PILE Load Tests on Pile.....	600
16.12	Cyclic Load Test	601
16.13	Correlations with Penetration Test Data	602
	<i>Objective Brain Teasers</i>	603
	<i>Conventional Brain Teasers</i>	609



Properties of Soils

2.1 INTRODUCTION

Soil is essentially made up of solid particles, with spaces or voids in between. The assemblage of particles in contact is usually referred to as the 'soil matrix' or the 'soil skeleton'. The intermittent void spaces are filled up by either air or water or both air and water. This means that an element of 'soil' may be considered as a three-phase material, comprising of some solid (soil grains), some liquid (pore water) and some gas (pore air). The proportion of these phases affects the properties of soil.

2.2 PHASE DIAGRAM

- Soil mass, in general is a three phase system composed of solid, liquid and gaseous phase.
- Different phases present in soil mass cannot be separated. For better understanding, all three constituents are assumed to occupy separate spaces as shown in figure below.

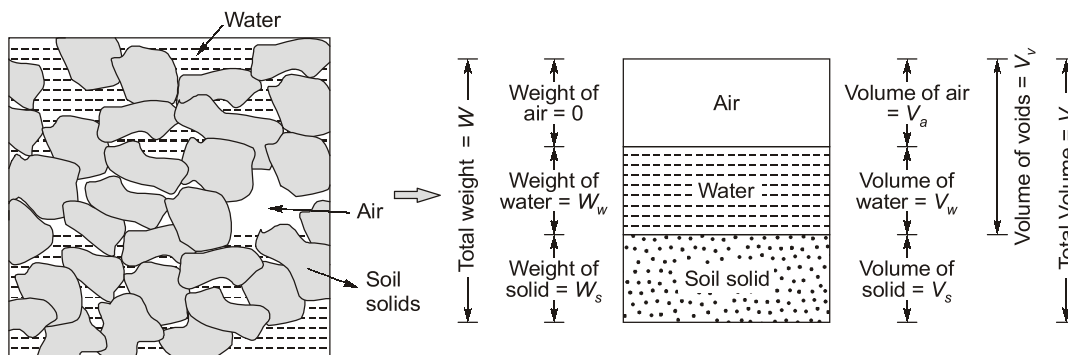
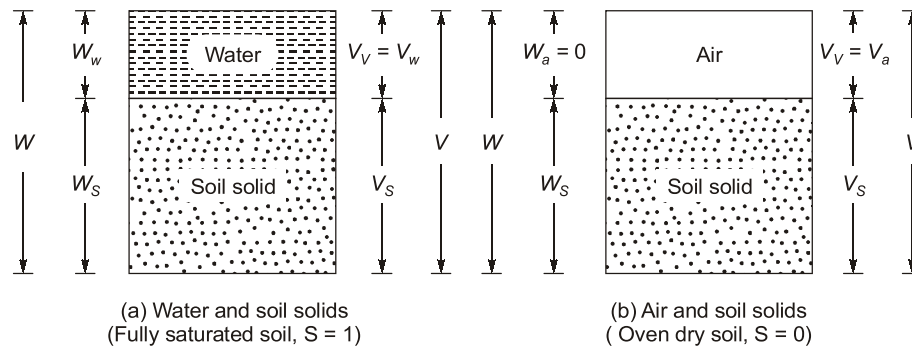


Fig. Three Phase diagram

- In phase diagrams, the weight of air is negligible as compared to soil solid and water and is thus assumed to be zero.
- The diagrammatic representation of the different phases in a soil mass is called the 'phase diagram', or 'block diagram'.
- A three-phase diagram is applicable for a partially saturated soil ($0 < S < 1$)
- When all the voids are filled with water, the sample becomes saturated and thus the gaseous phase is absent; whereas, in oven dry soil sample the liquid phase is absent. Thus, in saturated and oven dry soils, the three phase system reduces to two phase system.

**Fig.** Two Phase diagram

2.3 BASIC DEFINITIONS

2.3.1 Water Content (w)

- Water content (w) is also called moisture content. It is the ratio of weight of water (W_w) to the weight of soil solids (W_s).

$$w = \frac{W_w}{W_s}; \quad w \geq 0$$

- It is generally represented as a percentage.
- The water content of a oven dry soil is zero but natural water content for most soils is around 60%.
- There is no upper limit for water content. It can be greater than 100%.



- Fine-grained soils have higher values of natural moisture content as compared to coarse-grained soils.
- There are four possible forms of water present in soil:
 - Gravity water (free water): Added due to rain or flooding
 - Capillary water : Extracted through capillary action
 - Hygroscopic water : Water absorbed by oven dried sample when it is placed in open atmosphere
 - Structural water : Water bounded in crystalline structure of soil
On oven drying, gravity water, capillary water and hygroscopic water are removed but structural water remains present in soil mass.
- Water content in soil represents gravity water, capillary water and hygroscopic water, which can be removed on oven drying.
- Water content can also be represented in terms of total weight of soil mass.

$$w' = \frac{\text{weight of water}}{\text{Total weight of soil mass}} \times 100$$

$$w' = \frac{W_w}{W} \times 100 = \frac{M_w}{M} \times 100$$

Range of w' is $0 \leq w' < 100\%$

If we consider $w' = 100\%$, i.e., $W_w = W$ which is not possible in soil mass, hence, $w' \neq 100\%$.

Relationship between w and w' :

$$w' = \frac{W_w}{W} = \frac{W_w}{W_w + W_s} = \frac{W_w}{W_w \left[1 + \frac{W_s}{W_w} \right]} = \frac{1}{1 + \frac{1}{w}}$$

$$\therefore w' = \frac{w}{1 + w} \quad \text{or} \quad w = \frac{w'}{1 - w'}$$

Total weight of soil mass changes with change in weight of water. Hence engineering significance of ' w ' is more than w' because solids are stable quantity.

2.3.2 Void Ratio (e)

- The void ratio (e) of soil is defined as the ratio of the total volume of voids (V_v) to the volume of soil (V_s).

$$e = \frac{V_v}{V_s}; \quad e > 0$$

- It is generally expressed in decimal.
- In general $e > 0$, i.e. no upper limit for void ratio.
- Void ratio of fine grained soils is generally higher than that of coarse grained soils.



The individual void spaces in coarse grained soil are larger than fine grained soils; but the total void space is generally more in fine grained soils.

2.3.3 Porosity (n)

- The porosity (n) of a soil is defined as the ratio of volume of voids (V_v) to the volume of soil (V).

$$n = \frac{V_v}{V} \times 100\%$$

- It is generally expressed in percentage.
- In porosity, total volume of soil is used which includes volume of voids. Hence porosity (n) of soil cannot exceed 100%.
- The range of porosity is $0 < n < 100\%$.



Void ratio (e) and porosity (n) both have same significance but void ratio (e) is more widely adopted than porosity because volume of solid which is used in void ratio is more stable than total volume used in porosity.

2.3.4 Degree of Saturation (S)

- Degree of saturation (S) of a soil is defined as the ratio of the volume of water (V_w) to the volume of voids (V_v) in the soil mass.

$$S = \frac{V_w}{V_v} \times 100$$

- It is generally expressed in percentage.
- For dry soil, $S = 0\%$ and for fully saturated soil, $S = 100\%$, whereas partially saturated soil has $0 < S < 100\%$.



If soil is partially saturated, then total volume of soil and volume of void remain constant during variation of moisture content. If soil is super saturated due to addition of water beyond saturation, then volume of void and total volume increases. Hence void ratio will change but degree of saturation remains constant equal to 100%.

2.3.5 Air Content (a_c)

- It is defined as the ratio of the volume of air (V_a) to the total volume of voids (V_v) present in soil.

$$a_c = \frac{V_a}{V_v}$$

where,

V_a = volume of air in voids

V_v = volume of voids

- It is expressed in percentage.



- (i) For dry condition : $S = 0\%$ and $a_c = 100\%$
- (ii) For saturated condition : $S = 100\%$ and $a_c = 0\%$
- (iii) For partially saturated condition : $0 < S < 100\%$ and $0 < a_c < 100\%$.

Relationship between S and a_c

$$S = \frac{V_w}{V_v} = \frac{V_v - V_a}{V_v} = 1 - \frac{V_a}{V_v} = 1 - a_c$$

$$\therefore a_c + S = 1$$

2.3.6 Percentage Air Voids (n_a)

- Percentage air voids (n_a) is defined as the ratio of volume of air (V_a) to the total volume of soil mass (V).

$$n_a = \frac{V_a}{V} \times 100$$

- It is generally expressed in percentage.

Relation between n_a and a_c

$$n_a = \frac{V_a}{V} = \frac{V_a}{V} \times \frac{V_v}{V_v} = \frac{V_v}{V} \times \frac{V_a}{V_v}$$

$$n_a = n \times a_c$$

2.3.7 Unit Weights

(a) Bulk Unit Weight (γ_t or γ_b or γ)

- It is the ratio of total weight of soil to the total volume of soil mass.

$$\frac{\gamma_t}{\gamma_b} = \frac{W}{V} = \frac{W_s + W_w}{V_s + V_w + V_a}$$

- It is generally expressed as $\frac{\text{kN}}{\text{m}^3}$ or $\frac{\text{kgf}}{\text{cm}^3}$



- Bulk density is defined as the ratio of total soil mass to the total volume.

$$\rho_t = \frac{M}{V} = \frac{M_s + M_w}{V_s + V_w + V_a}$$

- It is generally expressed as $\frac{kg}{m^3}$ or g_{cc} .

(b) Dry Unit Weight (γ_d)

- It is the ratio of total dry weight of soil to the total volume of soil mass.

$$\gamma_d = \frac{\text{Dry weight of soil}}{\text{Total volume}} = \frac{W_{dry}}{V}$$

- Dry unit weight is used as a measure of denseness of soil. If dry unit weight value is more, it means the soil is more dense or compacted for same type of soil solids.



Dry density is defined as the ratio of total dry mass to the total volume.

$$\rho_d = \frac{M}{V} = \frac{M_{dry}}{V}$$

(c) Saturated Unit Weight (γ_{sat})

- It is defined as the ratio of total saturated weight of soil to the total volume of soil mass

$$\gamma_{sat} = \frac{W_{sat}}{V}$$



- Saturated density is defined as the ratio of total saturated soil mass to the total volume of soil mass.

$$\rho_{sat} = \frac{M_{sat}}{V}$$

- If the existing condition is dry, then its bulk unit weight will be same as of its dry unit weight.
 \therefore If $S = 0$, $\gamma_t = \gamma_d$
- If the existing condition is fully saturated then its bulk unit weight will be same as of its saturated unit weight.
 \therefore If $S = 100\%$, $\gamma_t = \gamma_{sat}$

(d) Submerged Unit Weight or Buoyant Unit Weight (γ_{sub} or γ')

- It is the ratio of buoyant weight of soil to the total volume of soil mass.

$$\gamma' = \frac{W_{sub}}{V}$$

- When soil is below water i.e. in submerged condition, a buoyant force acts on the soil solids which is equal in magnitude to the weight of water displaced by the soil solids. Hence the net weight of soil is reduced and reduced weight is known as buoyant weight or submerged weight.

$$\therefore \gamma' = \frac{W_{sub}}{V} = \frac{W_{sat} - V\gamma_w}{V} = \frac{W_{sat}}{V} - \frac{V\gamma_w}{V} = \gamma_{sat} - \gamma_w$$

- γ' is roughly half of saturated unit weight (γ_{sat})

NOTE

- Submerged density or buoyant density is defined as the total mass of soil submerged to the total volume of soil mass, $\rho' = \rho_{sat} - \rho_w$
- Soil in submerged condition will be in saturated condition also, but soil in saturated condition need not to be in submerged condition.
- Soil mass below the water table is saturated as well as submerged but soil mass in capillary zone is in saturated condition only.

(e) Unit Weight of Water (γ_w)

- It is the ratio of weight of water to the volume occupied by the water

$$\gamma_w = \frac{W_w}{V_w}$$

- Unit weight of water depends on its temperature. However, the unit weight of water is taken to be constant as 9.81 kN/m³ or 1g/cc for soil conditions.
- It is expressed in $\frac{kN}{m^3}$ or $\frac{kgf}{cm^3}$

(f) Unit Weight of Solids (γ_s)

- It is the ratio of weight of soil solids to the volume occupied by the soil solids.

$$\gamma_s = \frac{W_s}{V_s}$$

- It is expressed in $\frac{kN}{m^3}$ or $\frac{kgf}{cm^3}$



Order of unit weight of soil.

$$\therefore \gamma_s > \gamma_{sat} > \gamma_t > \gamma_d > \gamma'$$

2.3.8 True/absolute Specific Gravity (G or G_s)

- Specific gravity of soil solids (G) is the ratio of the weight of a given volume of solids to the weight of an equivalent volume of water at 4°C.

$$G \text{ or } G_s = \frac{W_s}{V_s \gamma_w} = \frac{\gamma_s}{\gamma_w} \quad \left[\because \gamma_s = \frac{W_s}{V_s} \right]$$

- The specific gravity of most of the inorganic soils lies in the range of 2.65 to 2.80.
- For organic soils, it lies in the range of 1.2 to 1.40.

 $[G]_{\text{fine grained}} > [G]_{\text{coarse grained}}$ \therefore Fine grained soil contains Al^{3+} , Fe, mg in clay minerals.**2.3.9 Apparent or Mass Specific Gravity (G_m)**

- Mass specific gravity is defined as the ratio of the total weight of a given volume of soil to an equivalent volume of water.

- Mass specific gravity can be defined as the ratio of bulk unit weight of soil to unit weight of water.

$$G_m = \frac{W_t}{V\gamma_w} = \frac{\gamma_t}{\gamma_w}$$

If soil is in saturated state,

$$G_m = \frac{\gamma_{sat}}{\gamma_w}$$

If soil is in dry state,

$$G_m = \frac{\gamma_d}{\gamma_w}$$



- Generally, specific gravity is represented either at 27°C or at 20°C. If test temperature is different than the standard temperature, then correction has to be done as follows—

$$G = \frac{\gamma_s}{\gamma_w}$$

$$\therefore G \times \gamma_w = \text{constant}$$

$$\Rightarrow G_{27^\circ\text{C}} \times \gamma_{w, 27^\circ\text{C}} = G_{T^\circ\text{C}} \times \gamma_{w, T^\circ\text{C}}$$

$$\therefore G_{27^\circ\text{C}} = G_{T^\circ\text{C}} \times \frac{\gamma_{w, T^\circ\text{C}}}{\gamma_{w, 27^\circ\text{C}}}$$

2.4 SOME IMPORTANT RELATIONSHIPS

2.4.1 Relation between W_s , W_w and w

From block diagram,

$$W = W_s + W_w + W_a$$

$$W = W_s + W_w + 0 \quad (\because W_a = 0)$$

$$W = W_s \left(1 + \frac{W_w}{W_s} \right)$$

$$W = W_s(1 + w) \quad (\because \text{Water content, } w = \frac{W_w}{W_s})$$

$$\therefore W_s = \frac{W}{1 + w}$$

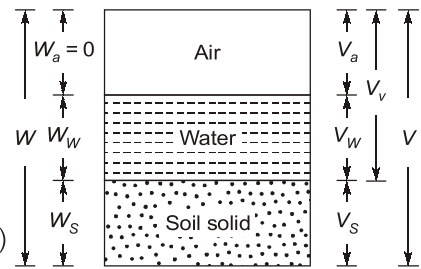


Fig. Three phase diagram

2.4.2 Relation between e and n

We know, Porosity, $n = \frac{V_v}{V} = \frac{V_v}{V_s + V_v} = \frac{\left(\frac{V_v}{V_s} \right)}{1 + \left(\frac{V_v}{V_s} \right)}$

$$\Rightarrow n = \frac{e}{1 + e} \quad \left(\because e = \frac{V_v}{V_s} \right)$$

$$\text{or } e = \frac{n}{1 - n}$$

2.4.3 Relation between e , S , w and G_s

We know,

$$\text{Void ratio, } e = \frac{V_v}{V_s}$$

$$\text{Also, } e = \frac{V_v}{V_s} = \frac{V_v}{V_w} \times \frac{V_w}{V_s} = \frac{V_v}{V_w} \times \frac{W_w / \gamma_w}{W_s / \gamma_s} = \frac{V_v}{V_w} \cdot \frac{W_w}{W_s} \cdot \frac{G_s \gamma_w}{\gamma_w} = \frac{1}{S} w G_s$$

$$e = \frac{w G_s}{S}$$

or

$$S e = w G_s$$

2.4.4 Relation between γ_t , G_s , e , w and γ_w

$$\gamma_t = \frac{W}{V} = \frac{W_s + W_w}{V_s + V_v} = \frac{W_s \left(1 + \frac{W_w}{W_s} \right)}{V_s \left(1 + \frac{V_v}{V_s} \right)}$$

$$\text{But } \frac{W_w}{W_s} = w \quad \text{and} \quad \frac{W_s}{V_s} = \gamma_s = G_s \gamma_w \quad \text{and} \quad \frac{V_v}{V_s} = e$$

$$\therefore \gamma_t = \frac{G_s \gamma_w (1 + w)}{1 + e} = \frac{\gamma_w (G_s + w G_s)}{1 + e}$$

$$\text{But } w G_s = S e$$

$$\therefore \gamma_t = \left(\frac{G_s + S e}{1 + e} \right) \gamma_w$$

Special Case (a): If soil is saturated, then

$$\gamma_t = \gamma_{\text{sat}} \quad \text{and} \quad S = 1$$

$$\gamma_{\text{sat}} = \left(\frac{G_s + 1 \times e}{1 + e} \right) \gamma_w$$

$$\therefore \gamma_{\text{sat}} = \left(\frac{G_s + e}{1 + e} \right) \gamma_w$$

Special Case (b): If soil is dry, then

$$\gamma_t = \gamma_d \quad \text{and} \quad S = 0$$

$$\gamma_d = \left(\frac{G_s + 0 \times e}{1 + e} \right) \gamma_w$$

$$\therefore \gamma_d = \frac{G_s \gamma_w}{1 + e}$$

Special Case (c): If soil is submerged, then

$$\gamma' = \gamma_{\text{sat}} - \gamma_w = \left(\frac{G_s + e}{1 + e} \right) \gamma_w - \gamma_w$$

$$\therefore \gamma' = \left(\frac{G_s - 1}{1 + e} \right) \gamma_w$$

2.4.5 Relation between γ_t, γ_d and w

$$\begin{aligned}\gamma_t &= \frac{W}{V} = \frac{W_s + W_w}{V} \\ \gamma_t &= \frac{W_s(1 + W_w / W_s)}{V} = \gamma_d(1 + w) \quad \left(\because \gamma_d = \frac{W_s}{V} \right) \\ \therefore \gamma_d &= \frac{\gamma_t}{1 + w}\end{aligned}$$

2.4.6 Relation between γ_d, G_s, w and n_a

$$\begin{aligned}V &= V_s + V_w + V_a \\ 1 &= \frac{V_s}{V} + \frac{V_w}{V} + \frac{V_a}{V} = \frac{V_s}{V} + \frac{V_w}{V} + n_a \\ 1 - n_a &= \frac{V_s}{V} + \frac{V_w}{V} = \frac{W_s / G_s \gamma_w}{V} + \frac{w W_s / \gamma_w}{V} \quad \left(\because V_w = \frac{w W_s}{\gamma_w} \right) \\ &= \frac{\gamma_d}{G_s \gamma_w} + \frac{w W_s / \gamma_w}{V} = \frac{\gamma_d}{G_s \gamma_w} + \frac{w \gamma_d}{\gamma_w} = \frac{\gamma_d}{\gamma_w} \left(w + \frac{1}{G_s} \right) \\ \therefore \gamma_d &= \frac{(1 - n_a) G_s \gamma_w}{1 + w G_s}\end{aligned}$$

Special Case (a): When $n_a = 0$, then soil become fully saturated at a given water content

Hence
$$\gamma_d = \frac{G_s \gamma_w}{1 + w G_s}$$

or
$$\gamma_{\text{sat}} = \left(\frac{G_s + e}{1 + e} \right) \gamma_w$$

2.4.7 Relation between S, w, G_s, γ_t and γ_w

$$\begin{aligned}\gamma_t &= \left(\frac{G_s + Se}{1 + e} \right) \gamma_w \\ \frac{\gamma_t}{\gamma_w} &= \left(\frac{G_s + Se}{1 + e} \right) = \left(\frac{G_s + w G_s}{1 + \frac{w G_s}{S}} \right) \\ \left(1 + \frac{w G_s}{S} \right) &= \frac{G_s \gamma_w (1 + w)}{\gamma_t} \\ \frac{1}{G_s} \left(1 + \frac{w G_s}{S} \right) &= \frac{\gamma_w (1 + w)}{\gamma_t} \\ \frac{1}{G_s} + \frac{w}{S} &= \frac{\gamma_w (1 + w)}{\gamma_t} \\ \text{or } S &= \frac{w}{\frac{\gamma_w (1 + w)}{\gamma_t} - \frac{1}{G_s}}\end{aligned}$$

2.4.8 Relation between e , V_s and V_T

$$e = \frac{V_v}{V_s}$$

$$1 + e = 1 + \frac{V_v}{V_s}$$

$$1 + e = \frac{V_s + V_v}{V_s} = \frac{V_T}{V_s}$$

 \therefore

$$V_s = \frac{V_T}{1 + e}$$



$$1. \quad W_s = \frac{W}{1 + w}$$

$$3. \quad Se = wG$$

$$5. \quad \gamma_{\text{sat}} = \left(\frac{G + e}{1 + e} \right) \gamma_w$$

$$7. \quad \gamma' = \left(\frac{G - 1}{1 + e} \right) \gamma_w$$

$$9. \quad \gamma_d = \frac{\gamma_t}{1 + w}$$

$$11. \quad V_s = \frac{V_T}{1 + e}$$

$$13. \quad S + a_c = 1$$

$$2. \quad n = \frac{e}{1 + e} \text{ or } e = \frac{n}{1 - n}$$

$$4. \quad \gamma_t = \left(\frac{G + Se}{1 + e} \right) \gamma_w$$

$$6. \quad \gamma_d = \frac{G \gamma_w}{1 + e}$$

$$8. \quad \gamma_d = \frac{(1 - n_a)G \gamma_w}{1 + wG}$$

$$10. \quad S = \frac{w}{\frac{\gamma_w}{\gamma_t}(1 + w) - \frac{1}{G}}$$

$$12. \quad n_a = n \cdot a_c$$

Example 2.1

A soil sampler of volume 1000 cm^3 is used to collect soil samples. It was found that the sampler contains 2 kg soil with dry unit weight of 1800 kg/m^3 . If 300 g water is mixed to the soil, then what will be the water content of the sample?

Solution:

$$\gamma_d = 1800 \text{ kg/m}^3$$

Dry weight of soil (weight of soil solids),

$$\begin{aligned} W_s &= V \times \gamma_d \\ &= 1000 \times 10^{-6} \times 1800 = 1.8 \text{ kg} \end{aligned}$$

But actual weight of sample, $W = 2 \text{ kg}$

\therefore Weight of water before mixing additional water,

$$W_{w_1} = W - W_s = 2 - 1.8 = 0.2 \text{ kg}$$

After mixing 300 g of water, the total weight of water would be

$$W_{w_2} = 0.2 + 0.3 = 0.5 \text{ kg}$$

Thus, water content,

$$w = \frac{W_{w_2}}{W_s} \times 100 = \frac{0.5}{1.8} \times 100 = 27.8\%$$

Example 2.2

Consider the following statements in relation to the given sketch:

Volume (cc)		Weight (g)
0.2	Air	0
0.3	Water	0.3
0.5	Solids	1.0

1. Soil is partially saturated at degree of saturation = 60%
2. Void ratio = 40%
3. Water content = 30%
4. Saturated unit weight = 1.5 g/cc

Which of these statements are correct?

- (a) 1, 2 and 3 (b) 1, 3 and 4
(c) 2, 3 and 4 (d) 1, 2 and 4

Ans. (b)

1. Degree of saturation, $S = \frac{V_w}{V_v} \times 100 = \frac{0.3}{(0.3 + 0.2)} \times 100 = 60\%$

2. Void ratio, $e = \frac{V_v}{V_s} = \frac{(0.3 + 0.2)}{0.5} \times 100 = 100\%$

3. Water content, $w = \frac{W_w}{W_s} \times 100 = \frac{0.3}{1} \times 100 = 30\%$

4. Saturated unit weight, $\gamma_{\text{sat}} = \left(\frac{G + Se}{1 + e} \right) \gamma_w$

$$G = \frac{\gamma_s}{\gamma_w} = \left(\frac{W_s/V_s}{\gamma_w} \right) = \left(\frac{1/0.5}{1} \right) = 2$$

$$\therefore \gamma_{\text{sat}} = \left(\frac{2 + 1 \times 1}{1 + 1} \right) \times 1 = \frac{3}{2} = 1.5 \text{ g/cc}$$

Example 2.3

An oven dry soil has mass specific gravity of 1.5 g/cc. If bulk density of soil in its natural state is 2.0 g/cc, then the water content of soil in natural state will be

- (a) 50% (b) 25%
(c) 100% (d) 33.33%

Ans. (d)

For oven dry soil,

Mass specific gravity, $G_m = \frac{\gamma_d}{\gamma_w} = 1.5$

$$\begin{aligned} \therefore \quad \gamma_d &= 1.5 \text{ g/cc} \\ \text{Given, bulk density,} \quad \gamma_t &= 2.0 \text{ g/cc} \\ \text{Using,} \quad \gamma_d &= \frac{\gamma_t}{1+w} \\ 1.5 &= \frac{2.0}{1+w} \\ w &= \frac{2.0}{1.5} - 1 = 33.33\% \end{aligned}$$

Hence option (d) is correct.

Example 2.4

Consider the phase diagram of the soil given below:

The soil is completely saturated

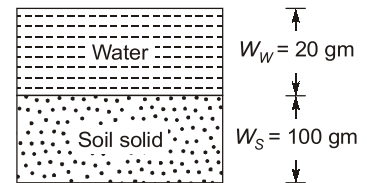
The specific gravity of soil solids is 2.6 (take unit weight of water as 10 kN/m^3).

Match List-I (Physical properties of soil) with List-II (Corresponding values) and select the correct answer using the codes given below.

List-I	List-II
1. Water content	A. 0.34
2. Void ratio	B. 0.52
3. Porosity	C. 20.53
4. Saturated density	D. 20%

Codes:

	1	2	3	4
(a)	A	C	B	D
(b)	B	A	D	C
(c)	C	A	B	D
(d)	D	B	A	C



Ans. (d)

$$\begin{aligned} 1. \text{ Water content,} \quad w &= \frac{W_w}{W_s} \times 100 = \frac{20}{100} \times 100 = 20\% \\ 2. \text{ Void ratio,} \quad e &= \frac{wG}{S} = \frac{0.2 \times 2.6}{1} = 0.52 \\ 3. \text{ Porosity,} \quad n &= \frac{e}{1+e} = \frac{0.52}{1+0.52} = 0.34 \\ 4. \text{ We know,} \quad \gamma_t &= \left(\frac{G + Se}{1+e} \right) \gamma_w \\ \text{For saturated density,} \quad \gamma_{\text{sat}} &= \left(\frac{G + 1 \times e}{1+e} \right) \gamma_w \\ &= \left(\frac{2.6 + 0.52}{1+0.52} \right) \times 10 = 20.53 \text{ kN/m}^3 \end{aligned}$$



**OBJECTIVE
BRAIN TEASERS**

- Q.1** In its natural condition, a soil sample has a mass of 2290 gm and a volume of $1.15 \times 10^{-3} \text{ m}^3$. After being completely dried in an oven, the mass of the sample is 2035 gm. The value of G for the soil is 2.68. Match **List-I** (Property) with **List-II** (Values) and select the correct answer using the codes given below:

List-I	List-II
A. Void ratio	1. 0.510
B. Porosity	2. 0.337
C. Degree of saturation	3. 0.657
D. Air content	4. 0.343

Codes:

	A	B	C	D
(a)	1	3	2	4
(b)	1	2	3	4
(c)	2	4	3	1
(d)	4	3	2	1

- Q.2** A mass of soil coated with a thin layer of paraffin wax weighs 700 gm and soil alone weighs 650 gm. When soil sample is immersed in water it displaces 400 mL of water. The specific gravity of soil is 2.65 and that of wax is 0.9 and water content is 20%, $\rho_w = 1000 \text{ kg/m}^3$. Void ratio of soil is
- (a) 0.81 (b) 0.59
(c) 0.73 (d) 0.69

- Q.3** Sieve analysis is done on a soil sample and following observation were made:

Size of sieve	% Retained
4.75 mm	36
75 micron	90

Size of particle for which 60% particles are finer = 5 mm
 Size of particle for which 30% particles are finer = 3 mm
 Size of particle for which 10% particles are finer = 1 mm
 On further testing the finer particles, it was found that:

Liquid limit = 50%

Plastic limit = 35%

Based on the above information, according to Indian soil classification system, the soil is

- (a) SW – SC (b) SP – SM
(c) GW – GC (d) None of these

- Q.4** A soil sample has a void ratio of 0.75, moisture content = 15%, $G_s = 2.6$ and $\gamma_w = 9.81 \text{ kN/m}^3$. The amount of water (in kN) required to be added per m^3 to make it saturated is _____ kN.

- Q.5** An embankment having a volume 200000 m^3 is to be constructed at a void ratio of 0.6. The soil is required to be excavated from a pit having a natural deposit void ratio of 1.0. Estimate the volume of excavated soil from the borrow pit in m^3 .
- (a) 160000 m^3 (b) 100000 m^3
(c) 200000 m^3 (d) 250000 m^3

- Q.6** The mass specific gravity of a fully saturated specimen of clay having a water content of 35% is 1.90. On oven drying, the mass specific gravity drops to 1.75. The specific gravity of clay particles and the shrinkage limit are respectively
- (a) 2.65 and 21% (b) 2.77 and 21%
(c) 2.77 and 28% (d) 2.65 and 28%

- Q.7** A clayey soil has saturated moisture content of 18%. The saturation percentage is 70%. The soil is allowed to absorb water and saturation increased to 92% after some time. Assuming specific gravity of soil to be 2.72, the water content of soil is latter case is
- (a) 20.26 (b) 23.66
(c) 21.24 (d) 25.61

- Q.8** A dry soil has mass specific gravity of 1.42. If the specific gravity of soil solids is 2.6, then the void ratio will be _____.

- Q.9** A sample of saturated clay has a porosity of 0.562. The void ratio of the clay is _____.

- Q.10** The pavement of a road is to be laid on a base course 500 mm thick. The base course has void ratio of 60% and degree of saturation, 50%. The

amount of rainfall needed to fully saturate the base course is

- (a) 93.75 mm (b) 60.15 mm
(c) 130.20 mm (d) 150 mm

Q.11 Consider the following statements in relation to the given table

Component	Volume (cm ³)	Weight (g)
Air	0.1	0.0
Water	0.3	0.3
Solids	0.6	1.50

Which of the following statements are CORRECT?

- Soil is partially saturated at degree of saturation = 50%
 - Void ratio = 66.7%
 - If $G = 2.65$, water content = 18.87%
- (a) 1 and 2 (b) 2 and 3
(c) 1 and 3 (d) 3 only

Q.12 In a wet soil mass, air occupies one eighth of its volume and water occupies one third of its volume. The void ratio and the air content of the soil are respectively:

- (a) 54% and 50% (b) 54% and 27.27%
(c) 60% and 25.0% (d) 85% and 27.27%

Q.13 A saturated soil sample has a volume of 26 cm³ at liquid limit. The shrinkage limit and liquid limit are 18% and 40% respectively. The specific gravity of solids is 2.6 and unit weight of water is 10 kN/m³.

The minimum volume which can be attained by the soil is _____ cm³.

Q.14 An embankment having a volume 200000 m³ is to be constructed at a void ratio of 0.6. The soil is required to be excavated from a pit having a natural void ratio of 1.0. Estimate the volume of excavated soil from the borrow pit in m³.

- (a) 160000 m³ (b) 100000 m³
(c) 300000 m³ (d) 250000 m³

Q.15 With the increased value of plasticity index of a soil, the quantity of lime required for its stabilisation will

- (a) increase
(b) decrease
(c) sometimes increase and sometimes decrease
(d) remain unaffected

Q.16 A sample of saturated clay has a porosity of 0.562. The void ratio of the clay is _____.

Q.17 The insitu void ratio of a granular soil deposit is 0.55. The maximum and minimum void ratios obtained for the same soil in the laboratory are 0.65 and 0.45 respectively. If specific gravity of solids is 2.67, then the relative density will be _____ %.

Q.18 The mass of a saturated soil sample is 150g and its mass when oven dried is 90g. The water content of the soil sample is _____ %.

Q.19 If w_L = Liquid limit, w_P = Plastic limit, I_P = Plasticity index, w = natural moisture content, then consistency index for a clayey soil (I_C) will be

- (a) $\frac{w_L - w}{I_P}$ (b) $\frac{w - w_L}{I_P}$
(c) $w_L - w_P$ (d) $0.5 w$

Q.20 Assertion (A): A compacted abutment of volume 250000 m³ is to be made from a soil taken from a borrow pit whose void ratio is 0.8. Void ratio in abutment is 0.6. Volume of soil taken from borrow pit is 281250 m³.

Reason (R): In both the volume of soil have equal number of solids.

Codes:

- (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 the correct explanation of A
(c) A is true but R is false
(d) A is false but R is true

Q.21 Assertion (A): In oven drying method, for soils containing significant amount of organic matter, a temperature range of 60°C – 80°C is recommended.

Reason (R): At higher temperature, organic matter in the soil tends to get oxidized.

Codes:

- (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 the correct explanation of A
- (c) A is true but R is false
- (d) A is false but R is true

ANSWER KEY

- | | | | |
|------------|-------------|---------|------------|
| 1. (b) | 2. (d) | 3. (d) | 4. (2.02) |
| 5. (d) | 6. (b) | 7. (b) | 8. (b) |
| 9. (1.283) | 10. (a) | 11. (b) | 12. (d) |
| 13. (18.7) | 14. (d) | 15. (a) | 16. (1.28) |
| 17. (50) | 18. (66.67) | 19. (a) | 20. (a) |
| 21. (a) | | | |

HINTS & EXPLANATIONS

1. (b)

Mass of the soil solid,

$$m_s = 2290 \text{ gm}$$

Mass of dry soil

$$m_d = 2035 \text{ gm}$$

Specific gravity

$$G = 2.68$$

Volume, $V = 1.15 \times 10^{-3} \text{ m}^3$

∴ Density of dry soil

$$\begin{aligned}\gamma_d &= \frac{2035 \times 10^{-3}}{1.15 \times 10^{-3}} \\ &= 1769.565 \text{ kg/m}^3\end{aligned}$$

$$\therefore \gamma_d = \frac{G \gamma_w}{1 + e}$$

$$\Rightarrow 1769.565 = \frac{2.68 \times 1000}{1 + e}$$

$$\Rightarrow e = 0.51$$

∴ Void ratio, $e = 0.51$

$$\text{Porosity } n = \frac{e}{1 + e} = 0.338$$

Water content

$$\begin{aligned}w &= \frac{m_w}{m_d} \\ &= \frac{2290 - 2035}{2035} = 0.125\end{aligned}$$

$$m_d = \frac{m}{1 + w}$$

$$\Rightarrow 2035 = \frac{2290}{1 + w}$$

$$\Rightarrow w = 0.125$$

$$\therefore wG = eS$$

$$\Rightarrow \frac{0.125 \times 2.68}{0.51} = S$$

$$\Rightarrow S = 0.657$$

∴ Degree of saturation = 0.657

$$\begin{aligned}\text{Air content, } &= 1 - S \\ &= 1 - 0.657 \\ &= 0.343\end{aligned}$$

2. (d)

$$M_{wax} = 700 - 650 = 50 \text{ gm}$$

$$\gamma_{wax} = 0.9 \times 1 = 0.9 \text{ gm/cc}$$

$$V_w = V_1 + V_{wax}$$

$$V_1 = V_w - V_{wax} = 400 - \frac{M_{wax}}{\gamma_{wax}}$$

$$V_1 = 400 - \frac{50}{0.9} = 344.4 \text{ mL}$$

$$\rho = \frac{M}{V_1} = \frac{650}{344.4} = 1.89 \text{ gm/cc}$$

$$\rho_d = \frac{\rho}{1 + w} = \frac{1.89}{1.20} = 1.57 \text{ gm/cc}$$

$$\rho_d = \frac{G \rho_w}{1 + e}$$

$$1.57 = \frac{2.65 \times 1}{1+e}$$

$$e = 0.69$$

3. (d)

% retained on 75 micron sieve is 90%

∴ Soil is coarse

$$\% \text{ Gravel} = 36$$

$$\% \text{ Sand} = 90 - 36 = 54$$

More than half of coarse fraction is sand

$$D_{60} = 5 \text{ mm}$$

$$D_{30} = 3 \text{ mm}$$

$$D_{10} = 1 \text{ mm}$$

$$C_u = \frac{D_{60}}{D_{10}} = \frac{5}{1} < 6$$

Finer analysis: It is poorly graded

$$I_p = \text{Liquid limit} - \text{Plastic limit}$$

$$= 50 - 35 = 15\%$$

$$\text{A-line, } I_p = 0.73 (w_L - 20)$$

$$= 0.73 (50 - 20) = 21.9$$

This will lie above A-line, therefore, it is clay.

Soil is SP - SC.

4. (2.02)

$$\text{We know that } \gamma_{\text{sat}} = \left(\frac{G+e}{1+e} \right) \gamma_w$$

$$\Rightarrow \gamma_{\text{sat}} = \left(\frac{2.60+0.75}{1+0.75} \right) \times 9.81 = 18.78$$

kN/m³

$$\text{we know, } e = \frac{wG}{S}$$

$$\Rightarrow S = \frac{wG}{e}$$

$$\Rightarrow S = \frac{0.15 \times 2.6}{0.75} = 0.52$$

$$\text{Also, } \gamma = \left(\frac{G+eS}{1+e} \right) \gamma_w$$

$$\Rightarrow \gamma = \left(\frac{2.6+0.75 \times 0.52}{1+0.75} \right) \times 9.81$$

$$\Rightarrow \gamma = 16.76 \text{ kN/m}^3$$

So water to be added in 1 m³ of soil to make it saturated is

$$\begin{aligned} \gamma_{\text{sat}} - \gamma &= 18.78 - 16.76 \\ &= 2.02 \text{ kN} \end{aligned}$$

5. (d)

Let V_1 and V_2 are the volumes of embankments and pit and e_1 and e_2 are their void ratios, V_{s1} and V_{s2} are the volumes of their soil solids.

$$e_1 = \frac{V_{v1}}{V_{s1}} \Rightarrow 1 + e_1 = 1 + \frac{V_{v1}}{V_{s1}}$$

$$\Rightarrow 1 + e_1 = \frac{V_{s1} + V_{v1}}{V_{s1}}$$

$$\Rightarrow 1 + e_1 = \frac{V_1}{V_{s1}} \Rightarrow V_{s1} = \frac{V_1}{1 + e_1}$$

$$\text{Similarly, } V_{s2} = \frac{V_2}{1 + e_2}$$

$$\therefore V_{s1} = \frac{V_1}{1 + e_1} = \frac{200000}{1 + 0.6} = \frac{200000}{1.6}$$

$$\text{and } V_{s2} = \frac{V_2}{1 + e_2} = \frac{V_2}{1 + 1.0} = \frac{V_2}{2.0}$$

$$\therefore V_{s1} = V_{s2}$$

$$\Rightarrow \frac{200000}{1.6} = \frac{V_2}{2.0}$$

$$\Rightarrow V_2 = 250000 \text{ m}^3$$

6. (b)

For fully saturated soil $S = 1$

We know that, $e = wG = 0.35 G$

$$\text{Also, } \frac{\gamma}{\gamma_w} = \left(\frac{G+eS}{1+e} \right)$$

$$\Rightarrow 1.9 = \frac{G+e}{1+e}$$

$$\text{Since, } e = 0.35 G$$

Since volume of solids are constant

$$\frac{V_{\text{borrow pit}}}{1 + e_1} = \frac{V_{\text{abutment}}}{1 + e_2} = \frac{250000}{1 + 0.6}$$

$$V_{\text{borrow pit}} = \frac{250000 \times 1.8}{1.6} = 281250 \text{ m}^3$$

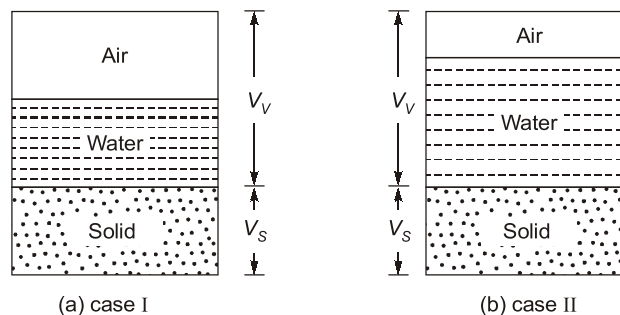


CONVENTIONAL BRAIN TEASERS

- Q.1** A clayey soil has saturated moisture content of 15.8%. The specific gravity is 2.72. Its saturation percentage is 70.8%. The soil is allowed to absorb water. After some time, the saturation increased to 90.8%. Find the water content of the soil in the later case.

Solution:

$$G = 2.72, S = 70.8, w = 15.8\%$$



In Case I,

$$\text{Void ratio, } e = \frac{wG}{S} = \frac{0.158 \times 2.72}{0.708} = 0.607$$

Since degree of saturation is within $0 < S < 100\%$. Hence volume of void remain same.

$$\therefore e_1 = e_2$$

$$\therefore w = \frac{0.908 \times 0.607}{2.72} = 0.2036 \text{ or } 20.26\%$$

- Q.2** A cohesive soils yields maximum dry density of 1.8 g/cc at an optimum moisture content of 16%. If $G_s = 2.65$, then find the degree of saturation. Also determine the maximum dry density which can be possible to achieved.

Solution:

Given,

$$\begin{aligned} \rho_{d, \max} &= 1.8 \text{ g/cc} \\ w &= 16 \% \text{ or } 0.16 \\ G &= 2.65 \end{aligned}$$

We know,

$$\rho_d = \frac{G\rho_w}{1+e}$$

$$\therefore e = \frac{2.65 \times 1}{1.8} - 1 = 0.472$$

Also,

$$S.e = wG$$

$$S = \frac{wG}{e} = \frac{0.16 \times 2.65}{0.472} = 0.8983 \text{ or } 89.83\%$$

Theoretical maximum dry density will be achieved when all the air present in the voids escaped out. i.e. all voids are just filled by water only.

\therefore For condition of theoretical maximum dry density,

$$S = 100\% \text{ or } 1$$

$$S.e = w.G$$

$$e = \frac{wG}{S} = \frac{0.16 \times 2.65}{1} = 0.424$$

$$\therefore \text{Theoretical maximum density, } \rho_{d,\max} = \frac{Gp_w}{1+e} = \frac{2.65 \times 1}{1+0.424} = 1.86 \text{ g/cc}$$

Q.3 You are a project engineer on a large dam project that has a volume of 800,000 m³ of selected fill, compacted such that the final void ratio in the dam is 0.80. The project manager delegates to you the important decision of buying the earth fill from one of the three suppliers. Which one of the three suppliers is the most economical and how much will you save.

Supplier A sells fill at ₹ 5 per m³ with $e = 1.50$

Supplier B sells fill at ₹ 10 per m³ with $e = 0.20$

Supplier C sells fill at ₹ 12 per m³ with $e = 1.60$

Solution:

Without considering void ratio, it would appear that supplier A is cheaper than B by ₹ 5 per m³.

$$\text{Volume of solid needed for dam site, } V_s = \frac{V}{1+e} = \frac{800,000}{1+0.80} = 444,444 \text{ m}^3$$

Volume of soil required to be taken out from suppliers,

$$\text{Supplier A, } V_A = V_s(1+e) = 444,444(1+1.50) = 1,111,110 \text{ m}^3$$

$$\text{Supplier B, } V_B = V_s(1+e) = 444,444(1+0.2) = 544,442 \text{ m}^3$$

$$\text{Supplier C, } V_C = V_s(1+e) = 444,444(1+1.6) = 1,155,555 \text{ m}^3$$

Cost of bills,

$$\text{Supplier A, } A = 1,111,110 \times 5 = ₹ 5,555,550$$

$$\text{Supplier B, } B = 544,442 \times 10 = ₹ 5,333,320$$

$$\text{Supplier C, } C = 1,155,555 \times 12 = ₹ 13,866,660$$

Therefore supplier B is more economical, and we save

$$= ₹ 5,555,550 - ₹ 5,333,320 = ₹ 222,230$$

Q.4 The fines fraction of a soil to be used for a highway near Hapur was subjected to a hydrometer analysis by placing 25 g of dry soil in 100 ml solution of water ($\mu = 0.01$ poise at 20°C). The specific gravity of the solid was 2.65.

(a) Estimate the maximum diameter D of the particle found at a depth of 5 cm after a sedimentation of 4 hour has elapsed, if the solution's concentration has reduced to 2 g/lit at the level.

(b) What % of the sample would have a diameter smaller than D ?