

CIVIL ENGINEERING

Soil Mechanics and Foundation Engineering



Comprehensive Theory
with Solved Examples and Practice Questions





MADE EASY Publications Pvt. Ltd.

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Soil Mechanics and Foundation Engineering

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EDITIONS

First Edition : 2015
Second Edition : 2016
Third Edition : 2017
Fourth Edition : 2018
Fifth Edition : 2019
Sixth Edition : 2020
Seventh Edition : 2021
Eighth Edition : 2022
Ninth Edition : 2023
Tenth Edition : 2024

Eleventh Edition : 2025

CONTENTS

Soil Mechanics and Foundation Engineering

CHAPTER 1

Origin of Soil and its Formation 1-7

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
	<i>Objective Brain Teasers</i>	7

CHAPTER 2

Properties of Soils8-71

2.1	Introduction	8
2.2	Phase Diagram.....	8
2.3	Basic Definitions.....	9
2.4	Some Important Relationships.....	14
2.5	Methods for Determination of Water Content.....	24
2.6	Determination of Specific Gravity of Soil Solids.....	27
2.7	Determination of In-Situ Unit Weight	29
2.8	Index Properties of Soils.....	33
2.9	Grain Size Analysis.....	34
2.10	Consistency of Clays (Atterberg's Limits)	43
2.11	Relative Density (I_p or RD).....	56
2.12	Sensitivity (S_t).....	59
2.13	Thixotropy	60
2.14	Activity (A_c)	60
2.15	Collapseability.....	61
2.16	Relationship between Atterberg Limits and Engineering Properties.....	62
	<i>Objective Brain Teasers</i>	64
	<i>Conventional Brain Teasers</i>	69

CHAPTER 3

Identification & Classification of Soils..... 72-84

3.1	Introduction	72
3.2	Field Identification of Soils.....	72
3.3	Engineering Classification of Soils.....	73
3.4	Classification of Coarse Grained Soil	76
3.5	Classification of Fine Grained Soil.....	79
	<i>Objective Brain Teasers</i>	83

CHAPTER 4

Soil Structure and Clay Minerals 85-92

4.1	Introduction	85
4.2	Soil Structure.....	85
4.3	Clay Minerals	85
4.4	Structure of Clay Minerals	86
4.5	Isomorphous Substitution	87
4.6	Types of Clay Minerals	87
4.7	Clay Water Relationship.....	88
4.8	Clay Particle Interaction	89
4.9	Soil Structure.....	90
4.10	Types of Soil Structures	90
	<i>Objective Brain Teasers</i>	92

CHAPTER 5

Soil Compaction93-115

5.1	Introduction	93
5.2	Principles of Compaction	93
5.3	Difference between Compaction and Consolidation.....	94
5.4	Advantages of Compaction	94

5.5	Laboratory Compaction.....	94
5.6	Comparison of Standard and Modified Proctor Test.....	96
5.7	Zero Air Void Line.....	98
5.8	Constant Percentage Air Void Lines.....	99
5.9	Factors Affecting Compaction.....	101
5.10	Compaction Behaviour of Sand.....	103
5.11	Effect of Compaction on Properties of Soils.....	104
5.12	Field Compaction and Equipment.....	106
5.13	Evaluation of Compaction.....	106
5.14	Compaction Quality Control.....	107
5.15	Settlement During Compaction.....	108
	<i>Objective Brain Teasers</i>	111
	<i>Conventional Brain Teasers</i>	114

CHAPTER 6

Principle of Effective Stress, Capillarity and Permeability..... 116-165

6.1	Introduction.....	116
6.2	Total Stress, Pore Pressure and Effective Stress.....	116
6.3	Physical Significance of Effective Stresses.....	118
6.4	Effective Stress in Partially Saturated Soils.....	119
6.5	Capillarity in Soils.....	120
6.6	Geostatic Stresses in Soils.....	124
6.7	Effect of Water Table Fluctuations on Effective Stress..	132
6.8	Permeability of Soils.....	134
6.9	Determination of Coefficient of Permeability.....	138
6.10	Factors Affecting Permeability.....	152
6.11	Coefficient of Absolute Permeability.....	154
6.12	Permeability of Stratified Soils.....	155
	<i>Objective Brain Teasers</i>	158
	<i>Conventional Brain Teasers</i>	164

CHAPTER 7

Seepage Through Soils..... 166-197

7.1	Introduction.....	166
7.2	Types of Head.....	166

7.3	Total Head.....	167
7.4	Seepage Pressure.....	167
7.5	Effects of Seepage Force on Effective Stress.....	168
7.6	Quick Sand Condition.....	173
7.7	Laplace Equations.....	179
7.8	Flow Nets.....	179
7.9	Application of Flow Nets.....	180
7.10	Flow Through Non-Homogeneous Section.....	184
7.11	Piping Failure and its Protection.....	185
7.12	Seepage Through Earthen Dams.....	186
	<i>Objective Brain Teasers</i>	192
	<i>Conventional Brain Teasers</i>	195

CHAPTER 8

Stress Distribution in Soils..... 198-222

8.1	Introduction.....	198
8.2	Boussinesq's Theory.....	198
8.3	Vertical Stress Distribution Diagrams.....	201
8.4	Westergaard's Theory.....	203
8.5	Comparison between Boussinesq and Westergaard Theories.....	205
8.6	Vertical Stresses beneath the loaded areas.....	206
8.7	Approximate Methods for Vertical Stress Computation.....	214
	<i>Objective Brain Teasers</i>	218
	<i>Conventional Brain Teasers</i>	220

CHAPTER 9

Compressibility and Consolidation of Soil..... 223-271

9.1	Introduction.....	223
9.2	Compressibility.....	223
9.3	Initial Settlement.....	224
9.4	Consolidation.....	224
9.5	Normally and Over Consolidated Soils.....	225
9.6	Compression Test.....	226

9.7	Determination of Compressibility Parameters	230
9.8	Preconsolidation Pressure	233
9.9	Field Consolidation Curve	234
9.10	Graph between Void Ratio and Effective Stress	235
9.11	Time Rate of Consolidation [Mechanics of Consolidation]	236
9.12	Terzaghi's Theory of One Dimensional Consolidation....	237
9.13	Compression Ratios	241
9.14	Settlement Analysis	242
9.15	Vertical Sand Drains.....	260
	Objective Brain Teasers.....	261
	Conventional Brain Teasers.....	267

CHAPTER 10

Shear Strength of Soils.....272-315

10.1	Introduction	272
10.2	Shear Strength of Soil	272
10.3	Mohr failure criterion	275
10.4	Factors Affecting Shear Strength.....	280
10.5	Measurement of Shear Strength.....	281
10.6	Direct Shear Test	281
10.7	Triaxial Test.....	285
10.8	Unconfined Compression Test.....	299
10.9	Vane Shear Test	301
10.10	Pore Pressure Parameters	303
10.11	Stress Path	305
10.12	Liquefaction of Soil.....	306
	Objective Brain Teasers.....	306
	Conventional Brain Teasers.....	311

CHAPTER 11

Earth Pressure and Retaining Walls316-373

11.1	Introduction	316
11.2	Retaining Structures.....	316
11.3	Types of Lateral Earth Pressure.....	318
11.4	Earth Pressure at Rest	319

11.5	Active and Passive Earth Pressure	322
11.6	Rankine's Theory:.....	324
11.7	Various Cases of Earth Pressure in Cohesionless Soil	326
11.8	Active and Passive Earth Pressure in Cohesive Soils	343
11.9	Coulomb's Wedge Theory.....	351
11.10	Sheet Pile Walls.....	353
11.11	Anchored Bulkhead.....	359
	Objective Brain Teasers.....	363
	Conventional Brain Teasers.....	367

CHAPTER 12

Stability of Slopes.....374-396

12.1	Introduction	374
12.2	Types of Slopes.....	374
12.3	Stability of Infinite Slopes.....	375
12.4	Definitions of Factor of Safety	381
12.5	Stability of Finite Slopes.....	383
12.6	Total Stress Analysis for a Purely Cohesive Soil.....	384
12.7	Swedish Method of Slices.....	386
12.8	Friction Circle Method	386
12.9	Effective Stress Analysis	388
12.10	Effective Stress Analysis by Bishop's Method	390
12.11	Taylor's Stability Number Method.....	390
	Objective Brain Teasers.....	392
	Conventional Brain Teasers.....	395

CHAPTER 13

Soil Exploration397-409

13.1	Introduction	397
13.2	Purpose of Soil Exploration.....	397
13.3	Stage in Sub-surface Exploration	397
13.4	Methods of Exploration	398
13.5	Types of Soil Samples.....	402
13.6	Soil Samplers.....	403

13.7	Disturbance of Soil Samplers	404
13.8	Number and Disposition of Trial Pits and Borings	407
	<i>Objective Brain Teasers</i>	408

CHAPTER 14

Soil Improvement..... 410-420

14.1	Introduction	410
14.2	Improvement Techniques	410
14.3	Reinforced Earth	413
14.4	Geotextiles : Definition and Types.....	415
14.5	Functions of Geotextiles	417
	<i>Objective Brain Teasers</i>	419

CHAPTER 15

Bearing Capacity and Shallow Foundation..... 421-471

15.1	Introduction	421
15.2	Types of Foundation.....	421
15.3	Selection of foundation	423
15.4	Bearing Capacity.....	425
15.5	Important Definitions.....	426
15.6	Mode of Shear Failure.....	427
15.7	Methods to Determine Bearing Capacity	429
15.8	Analytical Methods.....	429
15.9	Terzaghi's Method.....	432
15.10	Skempton's Method	447
15.11	Meyerhoff's Method.....	449

15.12	Plate load test	453
15.13	Standard Penetration Test.....	456
15.14	Cone penetration test.....	462
15.15	Settlement of Shallow Foundations	463
15.16	Heave of the Bottom of the Cut in Clay.....	464
	<i>Objective Brain Teasers</i>	465
	<i>Conventional Brain Teasers</i>	470

CHAPTER 16

Deep Foundation..... 472-515

16.1	Introduction	472
16.2	Floating Foundation.....	474
16.3	Classification of Piles	474
16.4	Bearing Capacity of Pile	477
16.5	Static Method for Ultimate Bearing Capacity of Piles.....	479
16.6	Dynamic Method.....	485
16.7	Under-reamed Piles	488
16.8	Group Action of Piles	490
16.9	Negative Skin Friction.....	500
16.10	Design of Pile Group.....	503
16.11	PILE Load Tests on Pile.....	504
16.12	Cyclic Load Test	505
16.13	Correlations with Penetration Test Data	506
	<i>Objective Brain Teasers</i>	507
	<i>Conventional Brain Teasers</i>	513

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.

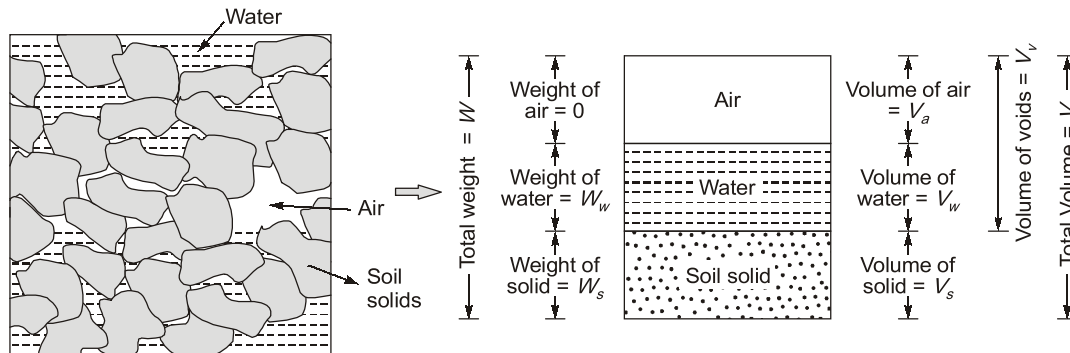


Fig. Three Phase diagram

- 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.

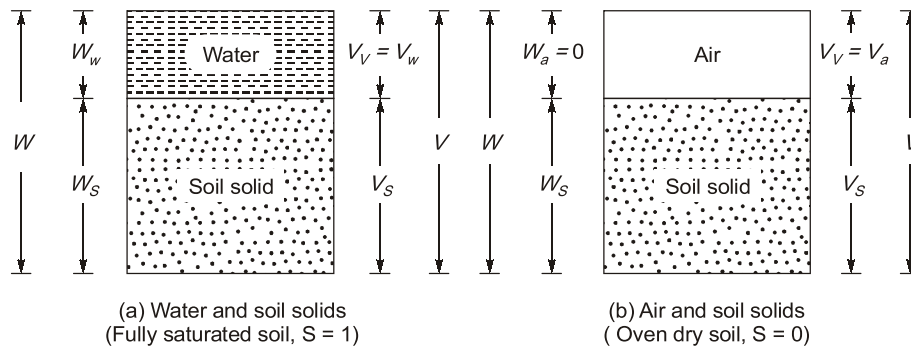


Fig. Two Phase diagram

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 $\frac{kgf}{cm^3}$



NOTE

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.



NOTE

$$[G]_{\text{fine grained}} > [G]_{\text{coarse grained}}$$

\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,

$$W = W_s + W_w + W_a$$

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

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

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

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

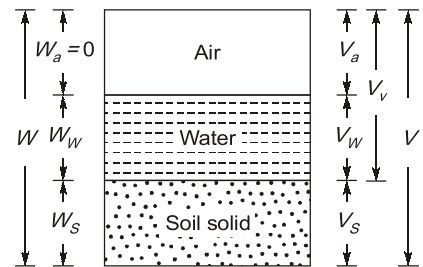


Fig. Three phase diagram

2.4.2 Relation between e and n

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

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

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

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

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

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

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

$$\gamma_t = \frac{W}{V} = \frac{W_s + W_w}{V}$$

$$\gamma_t = \frac{W_s(1 + W_w / W_s)}{V} = \gamma_d(1 + w) \quad \left(\because \gamma_d = \frac{W_s}{V} \right)$$

$$\therefore \gamma_d = \frac{\gamma_t}{1 + w}$$

2.4.6 Relation between γ_d, G_s, w and n_a

$$V = V_s + V_w + V_a$$

$$1 = \frac{V_s}{V} + \frac{V_w}{V} + \frac{V_a}{V} = \frac{V_s}{V} + \frac{V_w}{V} + n_a$$

$$1 - n_a = \frac{V_s}{V} + \frac{V_w}{V} = \frac{W_s / G_s \gamma_w}{V} + \frac{w W_s / \gamma_w}{V} \quad \left(\because V_w = \frac{w W_s}{\gamma_w} \right)$$

$$= \frac{\gamma_d}{G_s \gamma_w} + \frac{w W_s / \gamma_w}{V} = \frac{\gamma_d}{G_s \gamma_w} + \frac{w \gamma_d}{\gamma_w} = \frac{\gamma_d}{\gamma_w} \left(w + \frac{1}{G_s} \right)$$

$$\therefore \gamma_d = \frac{(1 - n_a) G_s \gamma_w}{1 + w G_s}$$

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

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

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

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

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

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

or
$$S = \frac{w}{\frac{\gamma_w (1 + w)}{\gamma_t} - \frac{1}{G_s}}$$

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),

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

But actual weight of sample,

$$W = 2 \text{ kg}$$

\therefore Weight of water before mixing additional water,

$$W_{w1} = W - W_s = 2 - 1.8 = 0.2 \text{ kg}$$

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

$$W_{w2} = 0.2 + 0.3 = 0.5 \text{ kg}$$

Thus, water content,

$$w = \frac{W_{w2}}{W_s} \times 100 = \frac{0.5}{1.8} \times 100 = 27.8\%$$



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 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.14 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.15 A sample of saturated clay has a porosity of 0.562. The void ratio of the clay is _____.

Q.16 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.17 The mass of a saturated soil sample is 150g and its mass when oven dried is 90 g. The water content of the soil sample is _____ %.

Q.18 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.19 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.20 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. (d) 14. (a) 15. (1.28) 16. (50)
 17. (66.67) 18. (a) 19. (a) 20. (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, $V = 1.15 \times 10^{-3} \text{ m}^3$ \therefore Density of dry soil

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

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

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

$$\Rightarrow e = 0.51$$

 \therefore Void ratio, $e = 0.51$

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

Water content

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

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

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

$$\Rightarrow w = 0.125$$

$$\therefore wG = eS$$

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

$$\Rightarrow S = 0.657$$

 \therefore Degree of saturation = 0.657

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

2. (d)

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

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

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

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

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

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

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

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

$$\begin{aligned}1.57 &= \frac{2.65 \times 1}{1+e} \\ e &= 0.69\end{aligned}$$

3. (d)

% retained on 75 micron sieve is 90%

 \therefore 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

$$\begin{aligned}I_p &= \text{Liquid limit} - \text{Plastic limit} \\ &= 50 - 35 = 15\%\end{aligned}$$

$$\begin{aligned}\text{A-line, } I_p &= 0.73 (w_L - 20) \\ &= 0.73 (50 - 20) = 21.9\end{aligned}$$

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

Soil is SP - SC.

4. (2.02)

We know that

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

$$\Rightarrow \gamma_{\text{sat}} = \left(\frac{2.60+0.75}{1+0.75} \right) \times 9.81 = 18.78 \text{ kN/m}^3$$

We know, $e = \frac{wG}{S}$

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

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

$$\gamma_{\text{sat}} - \gamma = 18.78 - 16.76 = 2.02 \text{ kN}$$

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.

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

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

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

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

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

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, $e = wG = 0.35G$

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

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

Since, $e = 0.35G$

$$\Rightarrow 1.9 = \frac{G+0.35G}{1+0.35G}$$

$$\Rightarrow G = 2.77$$

On oven drying, the mass specific gravity = 1.75

So, $\frac{\gamma_d}{\gamma_w} = 1.75$

Shrinkage limit, $w_s = \left(\frac{\gamma_w}{\gamma_d} - \frac{1}{G} \right)$

$$\Rightarrow w_s = \left(\frac{1}{1.75} - \frac{1}{2.77} \right)$$

$$\Rightarrow w_s = 0.2104 = 21.04\%$$

7. (b)

$$w = 18\%, \quad G = 2.72, \quad S = 70\%$$

$$e = \frac{w \cdot G}{S} = \frac{0.18 \times 2.72}{0.7} = 0.699$$

After absorption,

$$S = 92\%$$

$$w = \frac{0.92 \times 0.699}{2.72} = 0.2366 = 23.66$$

8. (b)

We know that, $\gamma_d = \frac{G\gamma_w}{1+e}$ (i)

Also, $G_m = \frac{\gamma_d}{\gamma_w}$ (for dry soil)

$$\Rightarrow \gamma_d = 1.42\gamma_w$$

Put this value in (i)

$$\Rightarrow 1.42\gamma_w = \frac{G\gamma_w}{1+e}$$

$$\Rightarrow 1.42 = \frac{2.6}{1+e}$$

$$\therefore e = 0.83$$

9. (1.283)

Given: Porosity, $n = 0.562$ Formula of e in terms of n ,

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

$$\Rightarrow e = \frac{0.562}{1-0.562} = 1.283$$

10. (a)

$$\text{Degree of saturations, } S = \frac{V_w}{V_v} = 0.5 \quad \dots(i)$$

$$\text{Void ratio, } e = \frac{V_v}{V_s} = 0.6 \quad \dots(ii)$$

$$\text{Porosity, } n = \frac{e}{1+e} = 0.375 = \frac{V_v}{V} \quad \dots(iii)$$

$$\therefore \frac{V_w}{V} = 0.375 \times 0.5$$

(Multiplying (i) and (iii))

$$V_w = 0.1875 \times 500 = 93.75 \text{ mm}$$

11. (b)

$$V_a = 0.1 \text{ cc; } V_w = 0.3 \text{ cc}$$

$$W_w = 0.3 \text{ g; } V_s = 0.6 \text{ cc}$$

$$W_s = 1.5 \text{ g}$$

Degree of saturation,

$$S = \frac{V_w}{V_v} = \frac{0.3}{0.4} = 0.75 \text{ as } 75\%$$

$$\text{Void ratio, } e = \frac{V_v}{V_s} = \frac{0.4}{0.6} = 0.667 \text{ as } 66.7\%$$

$$\therefore G = 2.65$$

$$\Rightarrow wG = Se$$

$$\Rightarrow w = \frac{0.75 \times 0.667}{2.65} = 0.1887 \text{ or } 18.87\%$$

12. (d)

Let V = Volume of wet soil mass

$$\therefore \text{Volume of air, } V_a = \frac{V}{8};$$

$$\text{Volume of water, } V_w = \frac{V}{3}$$

$$\therefore V_s = V - \left(\frac{V}{8} + \frac{V}{3} \right) = 0.54V$$

 \therefore Air content,

$$a_c = \frac{V_a}{V_v} = \frac{\frac{V}{8}}{\frac{V}{8} + \frac{V}{3}} = 0.2727 \text{ or } 27.27\%$$

$$\text{Void ratio, } e = \frac{V_v}{V_s} = \frac{\frac{V}{8} + \frac{V}{3}}{0.54V} \simeq 0.85 \text{ or } 85\%$$

13. (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 volumes of their soil solidsrespectively ($V_{s1} = V_{s2}$),

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

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

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

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

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

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

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

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

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

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

14. (a)

Lime reacts with aluminates, silicates (pozzolanic material) present in soil and forms calcium silicate and calcium aluminate, compounds responsible for development of soil strength. So if PI increases, then amount of mineral material will be more in soil. Hence, amount of lime required will be more.

15. 1.28 (1.27 to 1.29)

Given,

Porosity, $n = 0.562$

Formula of e in terms of n

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

$$\Rightarrow e = \frac{0.562}{1-0.562} = 1.28$$

16. (50)

Given:

$$e = 0.55$$

$$e_{\max} = 0.65 \text{ (loosest state)}$$

$$e_{\min} = 0.45 \text{ (densest state)}$$

$$G = 2.67$$

$$\therefore \text{Relative density } (I_D) = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \times 100$$

$$= \frac{0.65 - 0.55}{0.65 - 0.45} \times 100 = \frac{0.10}{0.20} \times 100 = 50\%$$

17. 66.67 (66 to 67)

Mass of saturated soil sample (M) = 150 g

Mass of oven dried soil sample (M_s) = 90 g

Mass of water present in soil sample

$$(M_w) = 150 - 90 = 60 \text{ g}$$

\therefore Water content of soil sample,

$$w = \frac{M_w}{M_s} = \frac{60}{90} = \frac{2}{3} = 0.6667 \text{ or } 66.67\%$$

18. (a)

Consistency Index (I_c) is defined as

$$I_c = \frac{w_L - w}{I_P}$$

19. (a)

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 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,

$$\rho_{d, \max} = 1.8 \text{ g/cc}$$

$$w = 16\% \text{ or } 0.16$$

$$G = 2.65$$

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,

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

$$S.e = w.G$$

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

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

Q.2 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.3 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 ?

Solution:

Given,

$$W_1 = 25 \text{ g, } V = 1000 \text{ ml or } 1000 \text{ cc}$$

$$t = 4 \text{ hrs} = 14,400 \text{ sec, } H_e = 5 \text{ cm, } \mu = 0.01 \text{ Poise} = 0.001 \text{ Ns/m}^2$$

$$(a) \text{ Using Stoke's law, } V = \frac{\gamma_w(G-1)}{18\mu} D^2 = \frac{H_e}{t}$$

$$\therefore D = \sqrt{\frac{18\mu H_e}{\gamma_w(G-1)t}} = \sqrt{\frac{18 \times 0.001 \times 5 \times 10^{-2}}{9.81 \times (2.65-1) \times 14400}}$$

$$= 6.2 \times 10^{-5} \text{ m} = 0.062 \text{ mm}$$