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Civil Services Examination

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Contents

Geotechnical Engineering

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Chapter 8

Chapter 9

Chapter 10

■■■■

Geotechnical Engineering

01
CHAPTER

Properties of Soil and Classification

1.1 INTRODUCTION

Soil: The word Soil originated from a Latin word Solum, which means the upper layer of Earth (dug or plowed). This refers to the loose material lying on the Earth's surface which is formed from the disintegration of rocks and contains organic matter and also supports plant life. The word soil has different meanings in different professions which are as under:

- In agriculture, the above definition is used.
- In geology, it means disintegrated rock material overlying the parent rock.
- In civil engineering, it means an unconsolidated material composed of solid particles which may be organic or inorganic in nature produced by disintegration of rocks.

Difference between rock and soil: Both rock and soil consists of mineral grains but the bond between mineral grains in soil is much weaker as compared to the bond in rock.

Terzaghi defined soil as "natural aggregates of mineral grains which can be separated by a gentle mechanical means like agitation of water etc."

Soil mechanics: It is the branch of Civil Engineering which deals with the application of the laws of mechanics and hydraulics to engineering problems dealing with sediments and other unconsolidated accumulations of solid particles produced by the mechanical and chemical disintegration of rock.

Rock mechanics: It is the science that deals with the application of principles of mechanics to understand the behavior of rock masses. It has been developed because of situations where heavy loads from the structures on the ground have to be transferred to the rock below and also in situations involving underground structures.

Soil engineering: It is the branch of engineering which deals with the application of principles of soil mechanics to the engineering problems. It includes site investigations, design and construction of foundations, earth retaining structures and earth structures.

Foundation engineering: It is the part of soil engineering that deals exclusively with foundation of structures on the soils.

Geotechnical engineering: It has a much wider scope and refers to all the engineering problems involving soil, rock as foundation as well as construction material. It incorporates the application of principles of soil mechanics, rock mechanics, engineering geology, Soil Engineering and Rock Engineering to solve problems involving soils and rocks.

Applications of geotechnical engineering: Geotechnical engineering finds its application in a wide number of areas like:

- Shallow foundations
- Deep foundations
- Underground structures like tunnel
- Earth retaining structures
- Embankments and cuts for highway, railway etc.
- Earth and rock fill dams

1.1.1 Origin of Soil

Almost all the soils are formed by the disintegration of rocks either through physical, mechanical or chemical weathering. If weathered sediments remain over parent rock, then soil is called 'Residual soil' and weathered sediments transported and deposited at some other place are called 'Transported soil'.

The process of soil formation is called 'Pedogenesis'.

The soil formation is cyclic which is called 'Geological cycle'.

These are the stages in the geological cycle of soil formation in transported soil:

(1) weathering

(2) transportation

(3) deposition of weathered materials

(4) upheaval

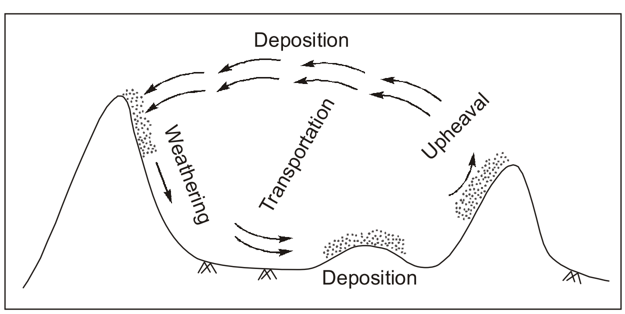
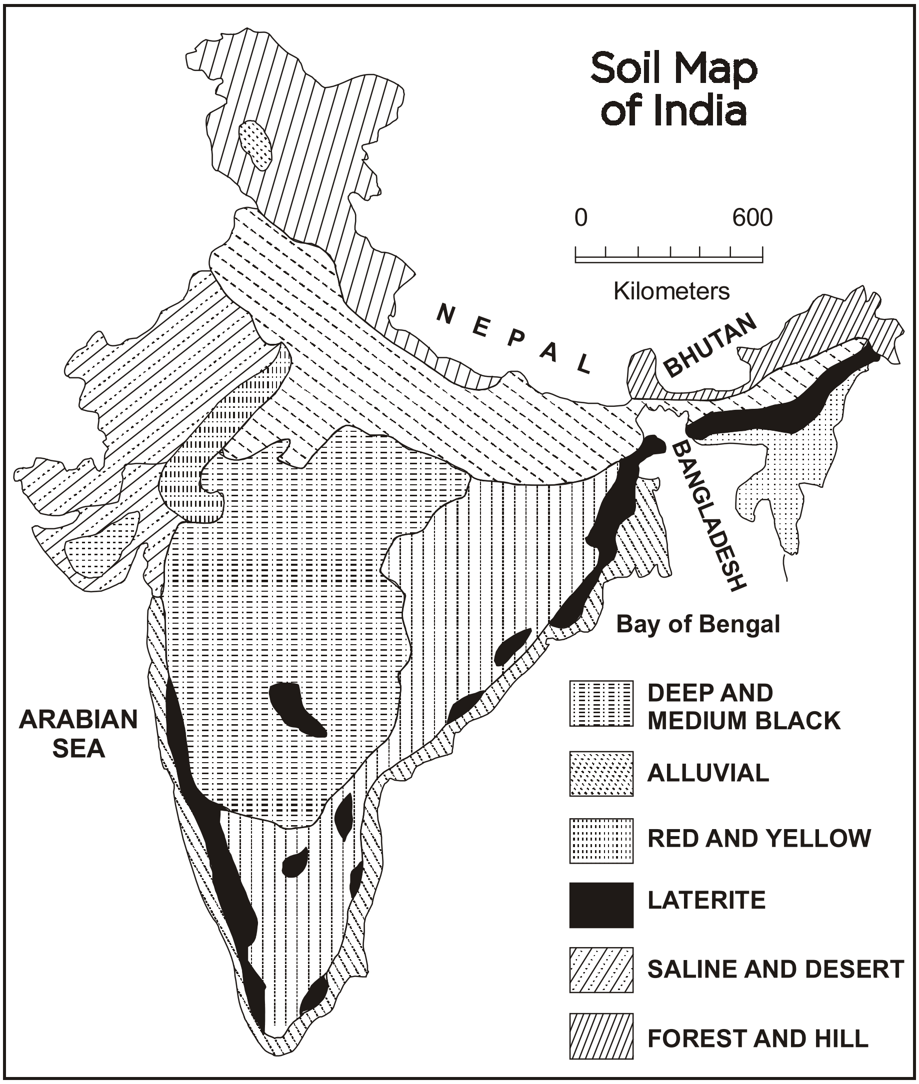


Fig. *Stages of Geological Cycle in case of transported soil*

1.1.2 Soil Deposits Commonly Found in India



1.1.3 Some of the Most Common Types of Soil

- **Loess:** This is wind blown uniformly graded fine soil. Loess is formed in arid and semi-arid regions. Its colour is yellowish brown and deposits of this soil are found in Rajasthan and North Gujarat.
- **Caliche:** It is cemented soil rich in calcium carbonate consisting of gravel, sand and silt. This is also wind blown in semi-arid climate and later on cemented by the calcium carbonate left out from the evaporation of capillary water.
- **Loam:** It is a mixture of sand, silt and clay in definite proportion which in some cases may consist of organic matter.
- **Cumulose:** Peaty (organic) soil is also called cumulose soil or muck. This is formed due to accumulation of organic content under waterlogged condition. It is generally found in the areas having deficient sewerage facilities or found after overflooding of the rivers.
- **Gumbo:** This is highly sticky, plastic and dark coloured soil.
- **Marl:** This is fine grained calcium carbonated soil of marine origin. This is formed due to decomposition of cell mass and bones of aquatic life.
- **Humus:** A dark brown, organic, amorphous earth of top soil, consisting of partly decomposed vegetative matter. The tiny pieces of rock and humus join to make various soils.

- **Peat:** It is highly organic soil containing almost entirely of vegetative matter invarying states of decomposition.
- **Tuff:** These are small grained slightly cemented volcanic ash that has been transported by wind or water.
- **Bentonite:** It is a clay formed by chemical weathering of volcanic ash which has high content of montmorillonite. Pulverized slurry of bentonite is highly plastic and is often used as a lubricant in drilling operations.
- **Kaolin (China Clay):** It is a very pure form of white clay, which is extensively used in ceramic industry.
- **Hard pan:** These are the types of soils that offer great resistance to the penetration of drilling tools during soil exploration. These are generally dense, well graded, cohesive aggregates of mineral particles.
- **Varved clays:** These are sedimentary deposits consisting of alternate thin layer of silt and clay. These clays are the result of deposition in lakes during periods of alternate high and low waters.
- **Till:** It is formed by glaciers and iceberg and may contain mixture of gravel, sand, silt and clay. It is a well grade soil.

1.2 PHASE DIAGRAM

- A soil mass is an aggregate of soil particles (with or without water) forming a porous structure. Soil particles in the soil mass are called as soil solids. The pores in the soil mass are called as voids. These voids may be filled with air, water or both.
- The diagrammatic representation of the different phases in a soil mass is called the 'phase diagram', or 'block diagram'.
- Different phases present in soil mass cannot be separated. For better understanding, all three constituents are assumed to occupy separate spaces as shown in the figure.
- Soil mass, in general is a three phase system composed of solid, liquid and gaseous phase.
- 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.

1.2.1 Three Phase System

Three phase system: A partially saturated soil mass consists of soil solids, water and air. These three physical states are idealized as three separate phases with soil solids in the bottom, water in the middle and air at the top as shown in figure. On one side of the three phase system, weight of solids (W_s), weight of water (W_w) and weight of air (W_a) (which is negligible) are shown and on the other side is shown the volume of solids (V_s), volume of water (V_w) and the volume of air (V_a).

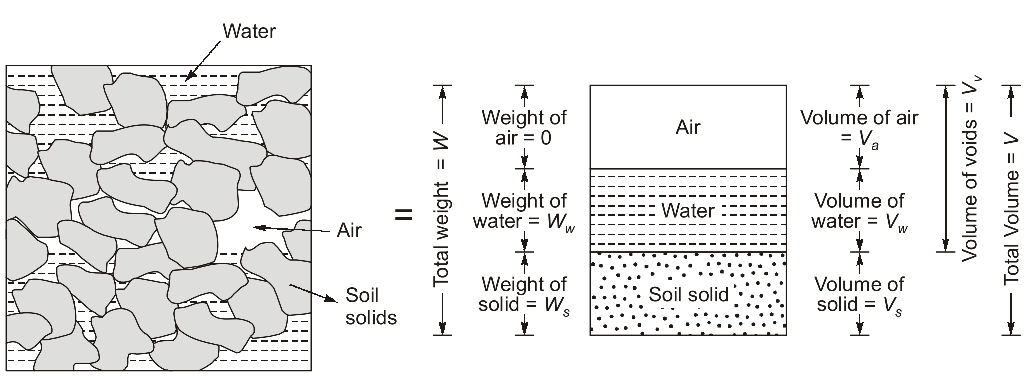
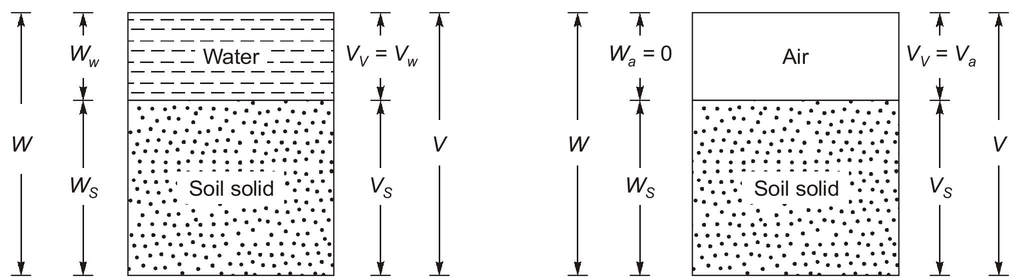


Fig. *Three Phase diagram*

1.2.2 Two Phase System

In two phase system, soil can either be fully dry (with soil solids and air only) or fully saturated (with soil solids and water only).



(a) Water and soil solids
(Fully saturated soil, S = 1)

(b) Air and soil solids
(Oven dry soil, S = 0)

Fig. *Two Phase diagram*

From the above figures, it can be deduced that:

$$V = V_s + V_v$$

$$V_v = V_w + V_a$$

$$W = W_s + W_v$$

$$W_v = W_w \qquad \text{(Since } W_a \simeq 0\text{)}$$

1.2.3 Basic Soil Terminologies

1. **Void ratio:** It is the ratio of volume of voids to the volume of solids and is denoted by *e*.

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

   Theoretically value of void ratio can vary from zero (when $V_v \to 0$) to infinite (when $V_s \to 0$). Although the individual void sizes in coarse grained soils is more, still for coarse grained soils void ratio varies from 0.5 to 0.9 and for fine grained soils, it varies from 0.7 to 1.5.

2. **Porosity:** It is the ratio of volume of voids to the total volume of soil mass and is denoted by *n*.

   Thus, $$n = \frac{V_v}{V}$$

   Since volume of voids (V_v) can vary from zero to total soil volume (V when $V_s \to 0$) and thus value of porosity (n) lies between zero and one. It is usually expressed in percentage.

   REMEMBER *Both void ratio and porosity are the measures of denseness or looseness of the soil. As the soil becomes denser, their value decreases because a denser soil implies lesser voids.*

3. **Degree of saturation:** It is the ratio of volume of water to the volume of voids in the soil mass and is denoted by *S*.

   Thus, $$S = \frac{V_w}{V_v}$$

   As volume of water occupies the volume of voids and thus volume of water cannot exceed the volume of voids. Therefore the degree of saturation always lies between zero and one (or zero and 100 in percentage).

For dry soil, $S = 0$
For fully saturated soil, $S = 1$ or 100%

4. **Air content:** It is the ratio of volume of air to the volume of voids present in the soil mass and is denoted by a_c. Thus,

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

But, $V_a = V_v - V_w$

Thus, $$a_c = \frac{(V_v - V_w)}{V_v} = 1 - S$$

5. **Percentage air voids:** It is the ratio of volume of air present in the soil mass to the total volume of soil mass and is denoted by n_a.

Thus, $$n_a = \frac{V_a}{V}$$

But, $$n = \frac{V_v}{V} \quad \text{...(i)}$$

And, $$a_c = \frac{V_a}{V_v} \quad \text{...(ii)}$$

Multiplying (i) and (ii),

$$n \cdot a_c = n_a$$

6. **Water content:** It is the ratio of weight of water in the soil mass to the weight of soil solids and is denoted by w.

Thus, $$w = \frac{W_w}{W_s}$$

Theoretically water content can vary from zero (when $W_w = 0$ in case of dry soil) to infinity (when $W_s \rightarrow 0$ i.e. soil contains too much water as compared to soil solids). Generally fine grained soils have more water content than coarse grained soils.

1.2.4 Densities and Unit Weights

1. **Bulk density:** It is the ratio of total mass of soil to its bulk volume and is denoted by ρ.

Thus, $$\rho = \frac{M}{V}$$

2. **Bulk unit weight:** It is the ratio of total weight of soil mass to its bulk volume and is denoted by γ.

Thus, $$\gamma = \frac{W}{V}$$

Now, $W = Mg$

Thus, $$\gamma = \frac{W}{V} = \frac{Mg}{V} = \rho g$$

3. **Dry density:** It is the ratio of mass of soil solids to the bulk volume of soil and is denoted by ρ_d.

Thus, $$\rho_d = \frac{M_s}{V}$$

As the soil can shrink on drying, so the dry density may not be equal to the bulk density of soil in dried condition.

4. **Dry unit weight:** It is the ratio of weight of soil solids to the bulk volume of soil and is denoted by ρ_d. Thus,

$$\gamma_d = \frac{W_s}{V}$$

But, $$W_s = M_s \cdot g$$

Thus, $$\gamma_d = \frac{W_s}{V} = \frac{M_s g}{V} = \rho_d g$$

5. **Saturated density:** It is the ratio of saturated mass of soil M_{sat} to the bulk volume of the soil and is denoted by ρ_{sat}.

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

For fully saturated soil mass, $\rho = \rho_{sat}$

So, saturated density is the bulk density of the soil when the soil is fully saturated.

6. **Saturated unit weight:** It is the ratio of weight of fully saturated soil mass W_{sat} to the bulk volume of the soil and is denoted by γ_{sat}.

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

For fully saturated soil mass, $\gamma = \gamma_{sat}$

7. **Specific gravity of soil particles:** It is defined as ratio of weight of a given volume of soil particles to the weight of an equivalent volume of water at a given temperature. Alternatively, it can be defined as ratio of unit weight of soil particles to unit weight of pure water at a given temperature. It is denoted by G_s or G.

Thus, $$G = \frac{W_s}{V_s \gamma_w} = \frac{\gamma_s}{\gamma_w} \text{ or } \frac{\rho_s}{\rho_w}$$

8. **Specific gravity of soil mass:** It is defined as ratio of bulk unit weight of soil mass to unit weight of pure water at a given temperature. It is denoted by G_m.

Thus, $$G_m = \frac{W}{V\gamma_w} = \frac{\gamma}{\gamma_w} \text{ or } \frac{\rho}{\rho_w}$$

9. **Submerged density:** It is the ratio of submerged mass of the soil to the bulk volume of the soil and is denoted by ρ_{sub} or ρ'.

When soil mass exists below water level, it is in a submerged condition. A buoyant force acts on the soil solids in this condition which is equal to the magnitude of mass of water displaced by the soil solids.

Thus, Buoyant force, $U = \rho_w \cdot V_s$

So, submerged mass of soil, $M_{sub} = M_s - U$

$$= V_s(G\rho_w) - V_s \rho_w \qquad \left(\because G = \frac{\rho_s}{\rho_w}\right)$$

So, $$\rho_{sub} = \frac{V_s \rho_w (G-1)}{V}$$

Alternatively, considering the equilibrium of entire volume,

$$M = M_{sat} = M_{st} V_v \cdot \rho_w$$

$$U = V\rho_w$$

So, $$\rho' = \frac{M_{sub}}{V} = \frac{(M_s + V_V\rho_w) - V\rho_w}{V}$$

or $$\rho' = \frac{M_{sat}}{V} - \rho_w$$

$\Rightarrow$ $$\rho' = \rho_{sat} - \rho_w$$

10. **Submerged unit weight:** It is the ratio of submerged weight of the soil to the bulk volume of the soil and is denoted by γ_{sub} or γ'.

Thus, $$\gamma_{sub} \text{ or } \gamma' = \frac{M_{sub}}{V} = \frac{(M - M_W)}{V} = \gamma - \gamma_w$$

Also, $$\gamma_{sub} = \rho_{sub} \cdot g$$

11. **Density of soil solids:** It is the ratio of mass of soil solids to the volume of soil solids and is denoted by ρ_s.

Thus, $$\rho_s = \frac{M_s}{V_s}$$

It is also known as mass density of solids.

12. **Unit weight of soil solids:** It is the ratio of weight of soil solids to the volume of soil solids and is denoted by γ_s.

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

Also, $$\gamma_s = \rho_s \cdot g$$

1.3 INTER-RELATIONSHIPS BETWEEN THE VARIOUS SOIL TERMINOLOGIES

1.3.1 Relation between W_s, W_w and W

From block diagram,

$$W = W_s + W_w + W_a$$

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

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

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

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

1.3.2 Relation between V, e and V_s

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

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

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

$$\therefore \qquad V_s = \frac{V}{1+e}$$

1.3.3 Relation between *e* and *n*

We know,

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

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

Also,

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

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

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

1.3.4 Relation between *e*, *S*, *w* and *G*

We know,

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

Also,

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

$$e = \frac{wG_s}{S}$$

or

$$Se = wG$$

1.3.5 Relation between γ_b, G_s, *e*, *w* and γ_w

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

But

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

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

But

$$w = \frac{Se}{G_s}$$

$$\therefore \qquad \gamma_b = \left(\frac{G_s + Se}{1+e}\right)\gamma_w$$

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

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

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

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

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

$$\gamma_b = \gamma_d \quad \text{and} \quad s = 0$$

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

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

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

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

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

1.3.6 Relation between γ_b, γ_d, w

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

$$\gamma_b = \frac{W_s(1 + W_w / W_s)}{V}$$

or
$$\gamma_d = \frac{\gamma_b}{1+w} \qquad \left(\because \gamma_d = \frac{W_s}{V}\right)$$

1.3.7 Relation between γ_d, G_s, w and n_a

$$V = V_s + V_w + V_a$$

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

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

$$= \frac{\gamma_d}{G_s\gamma_w} + \frac{wW_s / \gamma_w}{V}$$

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

or
$$\gamma_d = \frac{(1 - n_a)G_s \gamma_w}{1 + wG}$$

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

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

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

$$\gamma_b = \left(\frac{G_s + Se}{1+e}\right)\gamma_w$$

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

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

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

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

or

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

NOTE

1.	$W_s = \frac{W}{1+w}$	2.	$n = \frac{e}{1+e}$ or $e = \frac{n}{1-n}$
3.	$Se = wG$	4.	$\gamma_b = \left(\frac{G+Se}{1+e}\right)\gamma_w$
5.	$\gamma_{sat} = \left(\frac{G+e}{1+e}\right)\gamma_w$	6.	$\gamma_d = \frac{G\gamma_w}{1+e}$
7.	$\gamma' = \left(\frac{G-1}{1+e}\right)\gamma_w$	8.	$\gamma_d = \frac{(1-n_a)G\gamma_w}{1+wG}$
9.	$\gamma_d = \frac{\gamma_b}{1+w}$	10.	$S = \frac{w}{\frac{\gamma_w}{\gamma_b}(1+w)-\frac{1}{G}}$
11.	$V_s = \frac{V}{1+e}$		

1.4 METHODS OF DETERMINATION OF WATER CONTENT

1.4.1 Oven Drying Method

- This is the simplest and most accurate method.
- For inorganic soils, temperature is controlled between 105-110°C for 24 hours.
- For soil containing organic compounds, temperature is maintained about 60°C and if Gypsum is present, then temperature should be maintained at 80°C.
- At higher temperature, Gypsum loses its water of crystallization and organic soil may decompose and get oxidized. Usually 4-6 hrs are enough for sands to dry but 16-20 hrs are required for clay.
- If temperature is uncontrolled and more than 110°C, there is a danger of loss of structural water.

- Water content is calculated as follows:

  Let, W_1 = Weight of empty container

  W_2 = Weight of container + Moist soil

  W_3 = Weight of container + Dry soil

  W_w(weight of water) = $W_2 - W_3$

  W_s (weight of soil solids) = $W_3 - W_1$

$$\therefore \quad w = \frac{W_w}{W_s} \times 100$$

$$\Rightarrow \quad w = \frac{W_2 - W_3}{W_3 - W_1} \times 100$$

This method is accurate but time taking.

1.4.2 Pycnometer Method

- This is a quick method but it is less accurate than oven drying method.
- This method is used only when specific gravity of soil solids is known.
- A small weight, say 200 g to 400 g of soil is placed in a clean pycnometer whose capacity is 900 m*l*.
- Let W_1 = Weight of empty pycnometer bottle
  W_2 = Weight of pycnometer + soil
  W_3 = Weight of pycnometer + soil + water
  W_4 = Weight of pycnometer + water

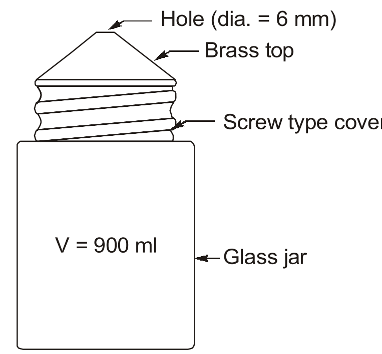


Fig. *Pycnometer*

Let G be specific gravity of soil solids,

Now, Water content, $w = \frac{W_w}{W_s} \times 100$

Weight of water $= (W_2 - W_1) - W_s$ ...(i)

If from W_3, the weight of solids W_s could be removed and replaced by the weight of an equivalent volume of water, the weight W_4 will be

$$W_4 = W_3 - W_s + \frac{W_s}{G\gamma_w} \cdot \gamma_w$$

$$W_s = (W_3 - W_4)\frac{G}{G-1} \quad \text{...(ii)} \left[\because V_s = \frac{W_s}{\gamma_s} \text{ and } G = \frac{\gamma_s}{\gamma_w}\right]$$

From (i) and (ii),

$$w = \left[\frac{(W_2 - W_1)}{(W_3 - W_4)}\left(\frac{G-1}{G}\right) - 1\right] \times 100$$

NOTE

- In view of the difficulty in removing entrapped air from the soil sample, this method is more suited for cohesionless soil where this can be achieved easily.
- Pycnometer method is suitable for coarse grained soil. But if it is used for fine grained soil, then instead of water kerosene should be used because kerosene has good wetting properties.

1.4.3 Calcium Carbide Method/Rapid Moisture Meter Method

- It is very quick method, takes only 5 to 7 minutes but may not give accurate results.
- A soil sample weight 4 - 6 gms is placed in moisture testing equipment. The equipment consists of a closed chamber in which calibrated scale is connected to measure pressure exerted which is directly co-related to water content.
- Calcium carbide powder (CaC_2) is added on the moist soil sample which reacts with the water and as a result acetylene gas is removed which exerts pressure.

  $CaC_2 + 2H_2O \rightarrow Ca(OH)_2 + C_2H_2 \uparrow$
- The water content recorded is expressed as a % of moist weight of soil, whereas actual water content is expressed as fraction of dry weight of soil

  Let, w_r = Moisture content recorded, expressed as fraction of moist weight of soil

  w = Actual water content

  Then, $$w = \frac{w_r}{1 - w_r} \times 100\%$$

1.4.4 Sand Bath Method

- It is a quick **field method**.
- This method is used when electric oven is not available.
- Soil sample is put in a container and dried by placing it on the sand bath, then it is heated over a kerosene stove.
- Depending upon the type of soil, drying takes about 20 - 60 minutes.
- Water content is determined similar to oven drying method.

  $$w = \frac{W_2 - W_3}{W_3 - W_1} \times 100$$

  where, W_1 = Weight of empty container

  W_2 = Weight of container + Moist soil

  W_3 = Weight of container + Dry soil
- Since temperature is uncontrolled, hence there is a chance of loss of structural water.

1.4.5 Alcohol Method

- It is also a quick method adopted in field.
- In this method, methylated spirit is mixed with the soil sample in order to increase the rate of evaporation and then methylated spirit is ignited.
- After it burns away completely, sample is cooled and weight of dry soil is obtained.

  $$w = \frac{W_1 - W_2}{W_2} \times 100$$

  where, W_1 = Weight of sample

  W_2 = Weight of soil after cooling of soil + methylated spirit mixture

This method is very rapid but less accurate.

REMEMBER This method should not be used for organic soils and for soils containing gypsum, large proportions of clay or any other calcareous materials.

1.4.6 Torsion Balance Method

- It is a laboratory method
- In this method, **infrared radiation is used for drying the soil sample**.
- Torsion balance moisture meter is used to weigh the soil sample.
- Drying temperature is kept at 110° ± 5°C.
- As the sample dries out under infrared lamp, the loss in weight is balanced by applying torque to one end of a torsion wire by means of a calibrated drum, which gives the weight of water lost by drying.
- The calibrated drum (or scale) gives the moisture content (w_r) as a % of moist weight of soil.

  Thus, actual water content,

$$w = \frac{w_r}{1-w_r} \times 100\%$$

- In this method, drying and weighing are done simultaneously.
- This method is rapid, accurate and most suitable for soils which quickly reabsorb moisture after drying.

1.4.7 Radiation Method

- This is an in-situ method to determine water content of soil.
- In this method, radioactive isotopes are used for the determination of water content of soil.
- A radiating device containing radioactive isotopes like Cobalt 60 is placed inside a capsule and lowered in a steel casing *A* as shown in figure. Steel casing has a small opening on one side through which rays can come out. A detector is placed inside another steel casing *B*, which also has an opening facing that of *A*.

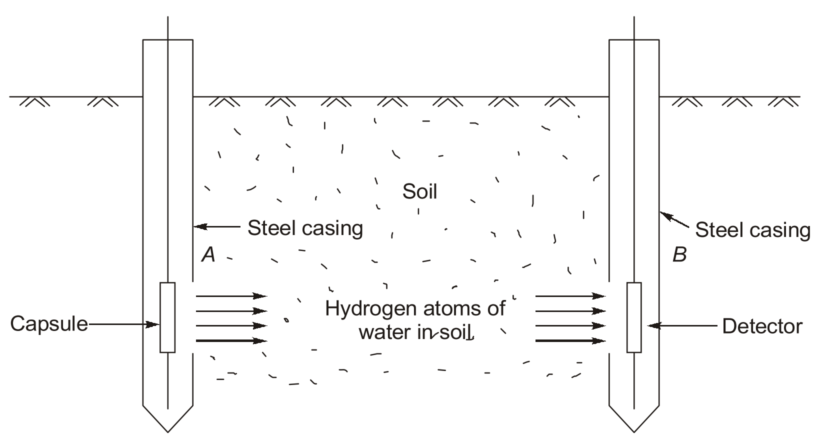


Fig. *Radiation Method*

- Neutrons are emitted by the radio-active material. The hydrogen atoms in water of the soil cause scattering of neutrons. As these neutrons strike with the hydrogen atom, they lose energy. The loss of energy is proportional to the quantity of water present in the soil. The detector is calibrated to give the water content directly.

  The method should be very carefully used as it may lead to γ-radiation problem.

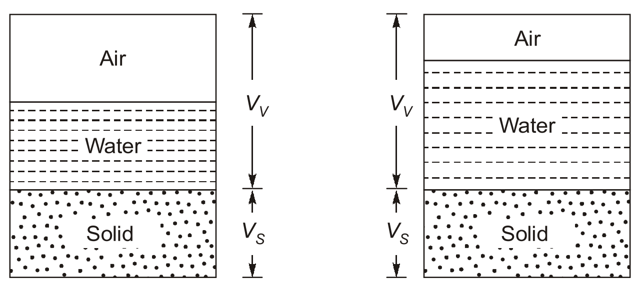
ILLUSTRATIVE EXAMPLES

EXAMPLE - 1.31

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*:**

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



(a) case I (b) case II

In Case I,

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.

$\therefore$ $$e_1 = e_2$$

$\therefore$ $$w = \frac{0.908 \times 0.607}{2.72} = 0.2036 \text{ or } 20.36\%$$

EXAMPLE - 1.32

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 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, $$S.e = wG$$

$$S = \frac{wG}{e} = \frac{0.16 \times 2.65}{0.472} = 0.89 \text{ or } 89\%$$

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.

∴ For condition of theoretical maximum dry density,

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

$$S.e = w.G$$

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

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

EXAMPLE - 1.33

You are a project engineer on a large dam project that has a volume of 800,000 m^3 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 ₹/m^3	with	e = 1.50
Supplier *B*	sells fill at 10 ₹/m^3	with	e = 0.20
Supplier *C*	sells fill at 12 ₹/m^3	with	e= 1.60

***Solution*:**

Without considering void ratio, it would appear that supplier *A* is cheaper than *B* by 5 ₹/m^3.

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

Volume of soil required to be taken out from suppliers,

Supplier *A*, $V_A = V_s(1 + e) = 4444{,}44\ (1 + 1.50) = 1{,}111{,}110\ m^3$

Supplier *B*, $V_B = V_s(1 + e) = 444{,}444\ (1 + 0.2) = 533{,}332\ m^3$

Supplier *C*, $V_C = V_s(1 + e) = 444{,}\ 444\ (1 + 1.6) = 1155{,}555\ m^3$

Cost of bills,

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

Supplier *B*, $B = 533{,}332 \times 10 = 5{,}333{,}320$ ₹

Supplier *C*, $C = 1155{,}555 \times 12 =$ ₹ 13,866,660

Therefore supplier *B* is more economical, and we save.

EXAMPLE - 1.34

The fines fraction of a soil to be used for a highway near Hapur was subjected to a hydrometer analysis be placing 25 g of dry soil in 100 m*l* solution of water (m = 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, $W_1 = 25$ g, $V = 1000$ ml or 1000 cc

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

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

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

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

(b) Concentration of solution $= \dfrac{2g}{l} = 2g$ soil solids in 1 litre

Unit weight of solution after 4 hrs,

$$\gamma = \frac{\text{Weight of solution}}{\text{Volume of solution}} = \frac{W_S + W_w}{V} = \frac{W_s + (V - V_S)\gamma_W}{V}$$

$$\gamma = \frac{2g + \left[V - \dfrac{W_S}{G\gamma_w}\right] \times \gamma_w}{V} \qquad \left[\because G = \frac{W_S}{V_S \gamma_w}\right]$$

$$\gamma = \frac{2 + \left[1000 - \dfrac{2}{2.65 \times 1}\right] \times 1}{1000} = 1.001 \text{ g/cc}$$

But $\gamma = 1 + \dfrac{R_H}{1000}$

$\therefore$ $R_H = 1.245$

% finer than particle of size 0.0615 m

$$\% = \frac{G}{G-1} \gamma_w \left(\frac{V}{W_1}\right)\left(\frac{R_H}{10}\right)\%$$

$$= \frac{2.65}{2.65-1} \times 1 \times 1\left(\frac{100}{25}\right) \times \left(\frac{1.245}{10}\right) = 8\%$$

PRACTICE QUESTIONS

Question : 1

The following observations were taken during a pipette analysis for the determination of particle size distribution of a soil sample:

(a) Depth below the water surface at which sample was taken = 120 mm
(b) Capacity of pipette = 10 ml
(c) Mass of sample when dried = 0.3 gm
(d) Time of taking sample = 7.5 minutes after start
(e) Volume of soil suspension in the sedimentation tube = 500 ml
(f) Dry mass of soil used in making suspension = 25 gm

Determine the coordinate of the point on the particle size distribution curve corresponding to above observations.

Take $G = 2.71$ and $\mu = 10.05$ millipoise, $\rho_w = 1$ gm/ml

[10 marks]

***Solution*:**

$$\text{Settling velocity} = \frac{H_e}{t} = \frac{(\gamma_s - \gamma_w)d^2}{18\mu}$$

H_e = Depth at which sample was taken, t = Time of settling

$$\frac{120 \times 10^{-3}}{7.5 \times 60} = \frac{(2.71 - 1) \times 9.81 \times 10^3 \times d^2}{18 \times 10.05 \times 10^{-4}}$$

$$d = 1.696 \times 10^{-5} \text{ m} = 0.01696 \text{ mm}$$

$$\text{Percentage finer} = \frac{\text{Concentration of suspension at anytime } t \times 100}{\text{Concentration of original suspension}}$$

$$= \left(\frac{0.3 \text{ gm}/10\text{m}l}{25 \text{ gm}/500 \text{ m}l}\right) \times 100 = 0.6 \times 100$$

Percentage finer = 60%

Co-ordinate of the point on the particle size distribution curve is (0.01696, 60%).

Question : 2

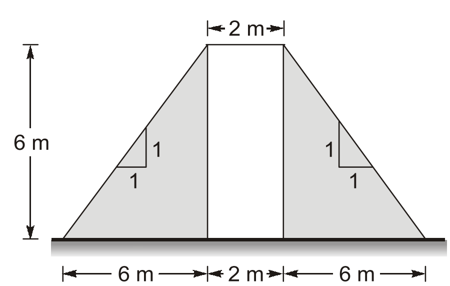
Earth is required to be excavated from borrow pits for building an embankment of height 6 m, top width 2 m and side slopes 1 : 1. The unit weight of undisturbed soil in wet condition is 18 kN/m³ and its natural water content is 8 percent. The dry density required in the embankment is 20 kN/m³ with a water content of 10%. The specific gravity of soil solids is 2.70. Estimate the quantity of earth required to be excavated in the borrow area to construct one meter length of the embankment. If each truck has a capacity to carry 80 kN per trip, what is the number of truck loads required per meter length of embankment? What are the values of porosity and degree of saturation on the embankment?

[15 marks]

***Solution*:**

Given data: r_1 = 18 kN/m³, w_1 = 8%, γ_{d_2} = 20 kN/m³ w_2 = 10%, G = 2.70, V_1 = ?

$$\text{Area of embankment} = \left(\frac{2+14}{2}\right) \times 6 = 48 \text{ m}^2$$



Volume of embankment = Area × Length = 48 × 1 = 48 m³ = V_2

Using subscript 1 and 2 for borrow pit and embankment respectively. All the symbols have their usual meanings

$$\therefore \quad \gamma_{d_2} = \frac{G\gamma_w}{1+e_2}$$

$$\Rightarrow \quad 20 = \frac{2.7 \times 9.81}{1+e_2}$$

$$\Rightarrow \quad e_2 = \frac{2.7 \times 9.81}{20} - 1 = 0.32$$

Now, porosity of the embankment soil,

$$n_2 = \frac{e_2}{1+e_2} = \frac{0.32}{1+0.32} = 0.2424$$

Degree of saturation of embankment soil can be given as

$$S_2 e_2 = w_2 G$$

$$\Rightarrow \quad S_2 = \frac{w_2 G}{e_2} = \frac{0.10 \times 2.70}{0.32} \times 100 = 84.37\%$$

Now, if V_1 is the volume of soil to be excavated from the borrow pit,

then $$\frac{V_1}{1+e_1} = \frac{V_2}{1+e_2} = V_s$$

But to calculate V_1, we require 'e_1' which can be calculated as

$$\gamma_{d_1} = \frac{G\gamma_w}{1+e_1} \quad \text{... (i)}$$

$$\gamma_{d_1} = \frac{\gamma_1}{1+w_1} \quad \text{... (ii)}$$

From (i) and (ii), we get $\frac{G\gamma_w}{1+e_1} = \frac{\gamma_1}{1+w_1}$

$$\Rightarrow \quad \frac{2.70 \times 9.81}{1+e_1} = \frac{18}{1+0.08}$$

$$\Rightarrow \quad e_1 = \frac{2.70 \times 9.81 \times 1.08}{18} - 1 = 0.589$$

Now, we have

$$\frac{V_1}{1+e_1} = \frac{V_2}{1+e_2}$$

$$\Rightarrow \quad V_1 = \left(\frac{1+e_1}{1+e_2}\right) \times V_2 = \left(\frac{1+0.589}{1+0.32}\right) \times 48 = 57.78 \text{ m}^3$$

Hence, 57.78 m^3 of earth is to be excavated in the borrow area.

Total weight of Borrow pit soil $= V_1 \times \gamma_2 = 57.78 \times 18 = 1036.8$ kN

$$\text{Number of truck loads required} = \frac{\text{Total weight of embankment soil}}{\text{Capacity of truck per trip}}$$

$$= \frac{1036.8}{80} = 12.96 \approx 13$$ number of truck loads, for construction of per meter length of embankment.

Question : 3

Classify the soil according to ISC system.

- Soil A : Liquid limit, W_L = 38% Plastic limit, W_P = 20%
  Percentage passing 4.75 mm sieve = 78% Percentage passing 0.075 mm sieve = 56%
- Soil B : Liquid limit, W_L = 18% Plastic limit, W_P = 12%
  Percentage passing 4.75 mm sieve = 72% Percentage passing 0.075 mm sieve = 53.50%

[10 marks]

Solution:

Soil A: $w_L = 38\%, \; w_P = 20\%$

Percentage passing 0.075 mm sieve = 56% > 50%

$\Rightarrow$ Soil is silt/clay

$$I_P = 38 - 20 = 18\%$$

As per A-line, $I_P = 0.73\,(w_L - 20) = 0.73\,(38 - 20) = 13.14\% < 18\%$

Soil lies above A-line in plasticity chart

$\Rightarrow$ Soil A is clay

$$W_L = 38\% \text{ lies between range } 35\% \text{ to } 50\%$$

Soil A can be classified as CI i.e. clay of intermediate compressibility.

Soil B :

Given, percentage 0.075 mm sieve > 50%

$\Rightarrow$ Soil silt/clay

$$w_L = 18\%, \ w_P = 12\%$$

$$\text{Plasticity index, } I_P = 18 - 12 = 6\%$$

As per A-line, $I_P = 0.73\,(w_L - 20) = 0.73\,(18 - 20) < 0$

Soil B lies above A-line, i.e. soil B is clay

$4 < I_P < 7$

$\Rightarrow$ Dual symbol must be given to the soil B.

Also, $w_L = 18\% < 35\%$

$\Rightarrow$ Soil B has low compressibility.

Best possible symbol given to soil B is CL-ML.

Question : 4

Laboratory sieve analysis was carried out on a soil sample using a complete set of standard IS sieves. Out of 750 gm of soil used in the test, 300 gm was retained on IS 600 μ sieve, 375 gm was retained on IS 500 μ sieve and the remaining 75 gm was retained on IS 425 μ sieve. Find the coefficient of uniformity of the soil and also classify the soil.

[10 marks]

Solution :

Total quantity of soil = 750 gm

Soil retained on IS 600 μ sieve = 300 gm

$$\text{\% retained on IS 600 μ sieve} = \left(\frac{300}{750}\right) \times 100 = 40\%$$

Soil passing through or finer than 600 μ = 100 – 40 = 60%

Hence, $D_{60} = 600\,\mu$

Soil retained on IS 500 μ sieve = 375 gm

$$\text{\% retained on IS 500 μ sieve} = \left(\frac{375}{750} \times 100\right) = 50\%$$

$$\text{\% finer than IS 500 μ sieve} = 100 - (50 + 40) = 10$$

Hence, $D_{10} = 500\,\mu$

$$\text{Coefficient of uniformly, } c_u = \left(\frac{D_{60}}{D_{10}}\right) = \left(\frac{600}{500}\right) = 1.20$$

Soil classification : Soil passing through 75 μ sieve = 0%.

Less than 50% is passing through 75 μ sieve so soil is coarse grained soil (either sand or gravel).

More than 50% of coarser fraction is passing through 4.75 mm sieve $\Rightarrow$ sand.

$$C_u < 6 \quad \Rightarrow \quad \text{Poorly graded}$$

Hence, soil is classified as SP.