



IES/GATE

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Civil Engineering

Volume - 7

Soil Mechanical



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CHAPTER
2

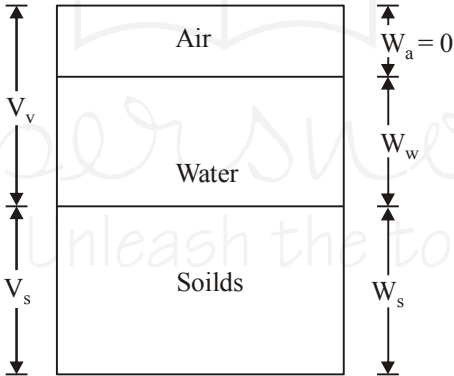
PROPERTIES OF SOILS

THEORY

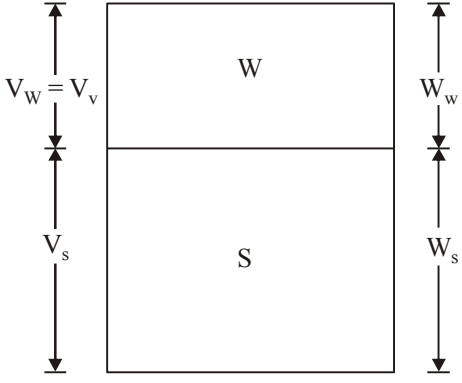
2.1 PROPERTIES OF SOILS

2.1.1 Phase Diagram

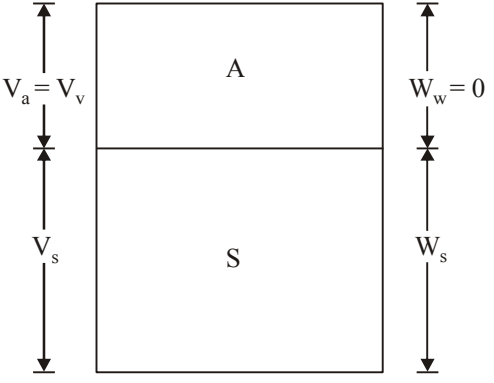
- Soil mass is in general a three phase system composed to solid, liquid and gaseous matter.
- The diagrammatic representation of the different phases in a soil mass is called the “phase diagram.”
- A 3-phase system is applicable for partially saturated soil whereas, a 2-phase system is for saturated and dry states of soil.



**3-Phase
(Partially Saturated)**



2-Phase (Saturated)



2-Phase (Dry)

2.1.2 Water Content

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

W_w = Weight of water

W_s = Weight of solids

There can be no upper limit to water content. i.e., $w \geq 0$

2.1.3 Void Ratio

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

V_v = Volume of voids

V_s = Volume of solids

Void ratio of fine grained soils are generally higher than those of coarse grained soils.

In general $e > 0$ i.e., no upper limit for void ratio.

2.1.4 Porosity (% voids)

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

V_v = Volume of voids

V = Total volume of soil

Porosity cannot equal to 100% i.e.,

$$0 < n < 100$$

Note : In comparison to porosity, void ratio is more frequently used because volume of solids remains same, whereas total volume changes.

2.1.5 Degree of Saturation

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

where

V_w = Volume of water

V_v = Volume of voids

$$0 \leq S \leq 100$$

for perfectly dry soil

$$S = 0$$

for Fully saturated soil

$$S = 100\%$$

2.1.6 Air Content

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

$$0\% \leq a_c \leq 100\%$$

Percentage air voids (n_a)

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

$$0\% \leq a_c < 100\%$$

Where

V_a = Volume of air

V = Total Volume

2.1.7 Unit Weight

(a) Bulk Unit Weight

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

Thus Bulk unit weight is total weight per unit volume.

(b) Dry Unit Weight

is the weight of soil solids per unit volume.

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

Dry unit weight is used as a measure of denseness of soil. More dry unit weight means more compacted soil.

(c) Saturated Unit Weight : It is the ratio of total weight of fully saturated soil sample to its total volume.

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

(d) Submerged Unit Weight : $\gamma' = \gamma_{\text{submerged}} = \gamma_{\text{sat}} - \gamma_{\text{water}}$. Buoyant unit weight (γ'). It is the submerged weight of soil solids per unit volume.

γ' is roughly $\frac{1}{2}$ of saturated unit weight.

Note : $\gamma_{\text{solid}} > \gamma_{\text{sat}} > \gamma_{\text{bulk}} > \gamma_{\text{dry}} > \gamma_{\text{sub}}$

(e) Unit Weight of Solids : It is the ratio weight of solids to the volume of solids present in given soil mass.

$$\gamma_{\text{solid}} = \frac{W_s}{V_s}$$

2.1.8 Specific Gravity

Absolute/true Specific Gravity : Specific gravity of soil solid (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.

$$G = \frac{W_s}{V_s \cdot \gamma_w} = \frac{\gamma_s}{\gamma_w}$$

Apparent or Mass Specific Gravity (G_m) : Mass specific gravity is the specific gravity of the soil mass and is defined as the ratio of the total weight of a given mass of soil to the weight of an equivalent volume of water.

$$G_m = \frac{W}{V\gamma_w} = \frac{\gamma}{\gamma_w}$$

2.2 SOME IMPORTANT RELATIONSHIPS

Relation between W_s , W and w :

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

Relation between e and n

$$n = \frac{e}{1+e} \text{ OR } e = \frac{n}{1-n}$$

Relation between e , w , G and S :

$$Se = w.G$$

Bulk unit weight (γ) in terms of G , e , w and γ_w

$$\gamma = \frac{G\gamma_w(1+w)}{(1+e)}$$

Saturated unit weight (γ_{sat}) in terms of G , e and γ_w (when $S = 1$)

$$\gamma_{sat} = \left[\frac{G+e}{1+e} \right] \cdot \gamma_w$$

Dry unit weight (γ_d) in terms of G , e and γ_w (when $S = 0$)

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

Submerged unit weight (γ') in terms of G , e

and γ_w

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

Relation between γ , γ_d and γ_w

$$\gamma_d = \frac{\gamma}{1+w}$$

2.3 METHODS FOR DETERMINATION OF WATER CONTENT

2.3.1 Pycnometer Method

- Quick method
- Capacity of pycnometer = 900 ml.
- This method is more suitable for cohesionless soils.
- Used when Specific gravity of soil solids is known.

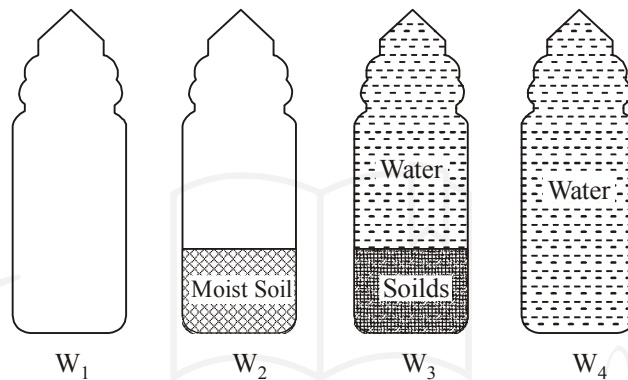
Let

W_1 = Wt. of empty dried pycnometer bottle

W_2 = Wt. of pycnometer + Moist Soil

W_3 = Wt. of pycnometer + Soil + Water

W_4 = Wt. of pycnometer + Water



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

$$\text{Weight of water} = (W_2 - W_1) - W_s \quad \dots(i)$$

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:

$$W_4 = W_3 - W_s + \frac{W_s}{G\gamma_w} \cdot \gamma_w \quad \left[\because V_s = \frac{W_s}{\gamma_s} \text{ and } G = \frac{\gamma_s}{\gamma_w} \right]$$

$$\Rightarrow W_s = (W_3 - W_4) \cdot \frac{G}{G-1} \quad \dots(ii)$$

From (i) and (ii)

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

2.3.2 Oven Drying Method

- Simplest and most accurate method
- Soil sample is dried in a controlled temperature (105 – 110° C).
- For organic soils, temperature is about 60° C.
- Sample is dried for 24 hrs.

- For sandy soils, complete drying can be achieved in 4 to 6 hrs.

Water content is calculated as :

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

where

W_1 = weight of container

W_2 = weight of container + moist sample

W_3 = weight of container + dried sample

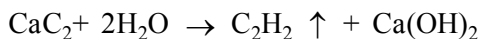
Weight of water = $W_2 - W_3$

Weight of solids = $W_3 - W_1$

2.3.3 Calcium Carbide Method/Rapid Moisture Meter Method

Quick method (required 5 to 7 minutes) but may not give accurate results.

The reaction involved is



Soil sample weight 4 – 6 gms.

The gauge reads water content with respect to wet soil.

i.e.,

$$w_r = \frac{W_w}{W_s + W_w}$$

Water content of the soil is determined indirectly from the pressure of acetylene (C_2H_2) gas formed.

Actual water content

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

2.3.4 Sand Bath Method

- Quick, field method
- Used when electric oven is not available.
- Soil sample is put in a container and dried by placing it in a sand bath, which is heated on kerosene stove.
- Water content is determined by using same formula as in oven drying method.

2.3.5 Torsion Balance Moisture Meter Method

- Quick method for use in laboratory.
- Infrared radiations are used for drying samples.
- **Principle** : The torsion wire is prestressed accurately to an extent equal to 100% of the scale reading. Then the sample is evenly distributed on the balance pan to counteract the prestressed torsion and the scale is brought back to zero. As the sample dries, the loss in weight is continuously balanced by the rotation of a drum calibrated directly to read moisture % on wet basis.

2.4 DETERMINATION OF SPECIFIC GRAVITY OF SOIL SOLIDS

- Pycnometer method is used.
- Instead of pycnometer. Density bottle (50 ml) OR Flask (500 ml) can also be used.

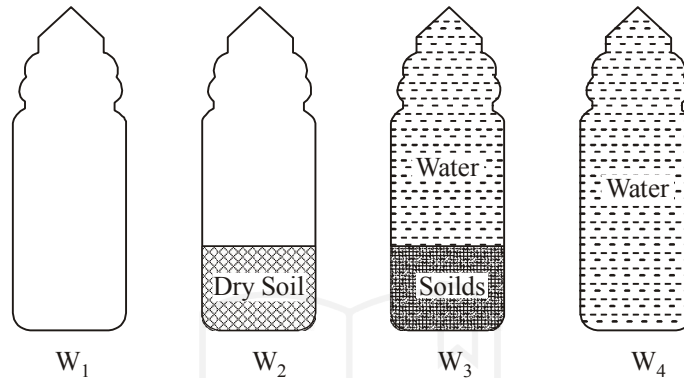
Let,

W_1 = Weight of empty pycnometer

W_2 = Weight of pycnometer + soil sample (oven dried)

W_3 = Weight of pycnometer + soil solids + water

W_4 = Weight of pycnometer + water



$$G = \frac{W_2 - W_1}{(W_2 - W_1) - (W_3 - W_4)}$$

⇒

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

Note : Specific gravity values are generally reported at 27° C (in India)

If T° C is the test temperature then Sp. Gr. at 27° C is given by,

$$G_{27^\circ\text{C}} = G_T \frac{\text{Unit weight of water at } T^\circ\text{C}}{\text{Unit weight of water at } 27^\circ\text{C}}$$

If kerosene (better wetting agent) is used instead of water then.

$$G = \frac{W_s}{W_s - W_3 + W_4} \times K \quad [K = \text{Sp. gr. of kerosene}]$$

G can also be determined indirectly by using shrinkage limit.

2.5 METHODS FOR THE DETERMINATION OF IN SITU UNIT WEIGHT

2.5.1 Core-Cutter Method

- Used in case of non-cohesive soils.
- Cannot be used in case of hard and gravelly soils.
- Method consists of driving a core-cutter (Volume = 1000 cc) into the soil and removing it, the cutter filled with soil is weighed. Volume of cutter is known from its dimensions and in situ unit weight

is obtained by dividing soil weight by volume of cutter. $\gamma = \frac{W}{V}$

- If water content is known in laboratory, the dry unit weight can also be computed.

$$\gamma_d = \frac{\gamma}{1 + w}$$

2.5.2 Sand Replacement Method

- Used in case of hard and gravelly soils.
- A hole in ground is made. The excavated soil is weighed. The volume of hole is determined by replacing it with sand. In situ unit weight is obtained by dividing weight of excavated soil with volume of hole.

2.5.3 Water Displacement Method

- Suitable for cohesive soils only, where it is possible to have a lump sample.
- A regular shape, well trimmed sample is weighed. (W_1). It is coated with paraffin wax and again weighed (W_2). The sample is now placed in a metal container filled with water upto the brim. Let the volume of displaced water be V_w . Then volume of uncoated specimen is calculated as,

$$V = V_w - \left(\frac{W_2 - W_1}{\gamma_p} \right)$$

where

γ_p = unit weight of paraffin wax

and bulk unit weight of soil

$$\gamma = \frac{W_1}{V}$$

2.6 GRAIN SIZE DISTRIBUTION

Grain size analysis/particle size analysis involves the following methods :

- (i) For coarse grained soils – sieve analysis further,
 - for coarser of coarse – Dry sieve analysis
 - for finer of coarse – Wet sieve analysis.
- (ii) For fine grained soils – sedimentation analysis,
 - It involves two methods
 - (a) Hydrometer method
 - (b) Pipette method.

2.6.1 Analysis of Coarse Grained Soils

(a) Sieve Analysis : (For Coarse Grained Soils)

- The fraction retained on 4.75 mm sieve is called the gravel fraction which is subjected to coarse sieve analysis.
- The material passing 4.75 mm sieve is further subjected to fine sieve analysis if it is sand or to a combined wet sieve and sedimentation analysis if silt and clay sizes are also present.
- **Concept of “Percentage finer”**

$$\% \text{ retained on a particular sieve} = \frac{\text{Weight of soil retained on that sieve}}{\text{Total weight of soil taken}} \times 100$$

Cumulative % retained = sum of % retained on all sieves of larger sizes and the % retained on that particular sieve.

“Percentage finer” than the sieve under reference = 100% – Cumulative % retained.

2.6.2 Analysis of Fine Grained Soils

Sedimentation Analysis : Most convenient for determining of grain size distribution of the soil fraction finer than 75 μm .

- The analysis is based on stokes’s law.
- If a single sphere is allowed to fall freely through a liquid of infinite extent, its vertical velocity is first increased rapidly under the action of gravity, but a constant velocity called the terminal velocity is reached with in a short time.
- According to stokes law, the terminal velocity is given by,

$$V = \frac{g}{18} \frac{\rho_s - \rho_w}{\mu} D^2$$

ρ_s = density of grains (g/cm^3)

ρ_w = density of water (g/cm^3)

μ = dynamic viscosity of water

g = acceleration due to gravity (cm/s^2)

D = Diameter of grain (cm)

- (i) By putting the values at 20° C, we get,

$$V \approx 91 D^2 \quad \text{.....at } 20^\circ \text{ C}$$

where v is in cm/s

and D is in mm .

- (ii) $V \approx 107 D^2 \quad \text{.....at } 27^\circ \text{ C}$

If ‘ h ’ the height through which particle falls in time ‘ t ’, then

$$\frac{h}{t} = k.D^2$$

$$\therefore \frac{D_1}{D_2} = \sqrt{\frac{h_1 \cdot t_2}{h_2 \cdot t_1}}$$

- Stokes law is applicable for spheres of diameter between 0.2 mm and 0.0002 mm.
- Spheres of diameter larger than 0.2 mm falling through water cause turbulence, whereas, for spheres with diameter less than 0.0002 mm. Brownian motion takes place and the velocity of settlement is too small for a accurate measurement.
- **Limitations of Stokes Law :** The analysis is based on the assumption that the falling grain is spherical. But in soils, the finer particles are never truly spherical.
- Stoke’s law considers the velocity of free fall of a single sphere in a suspension of infinite extent, whereas, the grain size analysis is usually carried out in a glass jar in which the extent of liquid is limited.
- The finer grains of the soil carry charge on their surface and have a tendency for floc formation. If the tendency to floc formation is not prevented, the diameter measured will be the diameter of the floc and not of the individual grain.

- **Analysis of Fine Grained Soils :** First step involved is preparation of soil sample, which is mixed with water and suspension is made.

Treatment given to soil sample :

- **Pre Treatment :** given before making of soil suspension to remove organic matters and calcium compounds.
- For organic matter – oxidizing agent is used (e.g., H₂O₂)
- For calcium compounds – Acids are used (e.g., HCl)
- **Post Treatment :** Given after preparation of soil suspension to break the flocss formed due to presence of surface electric charges.
- The dispersing (deflocculating) agents used are sodium hexameta phosphate or calgon, sodium oxalate, etc.
- The analysis is carried out by the Hydrometer method or the pipette method. The principle of the test is same in both methods. The difference lies only in the method of making observations.
- **Pipette Method :** In this method, the weight of solids per cc of suspension is determined directly by collecting 10 cc of soil suspension from a specified sampling depth.
- If m_d = dry mass (obtained after drying the sample) then, mass present in unit volume of pipette.

$$= \frac{m_d}{\text{vol. of pipette}(V_p)} = \frac{m_d}{10\text{ml.}(V_p)}$$

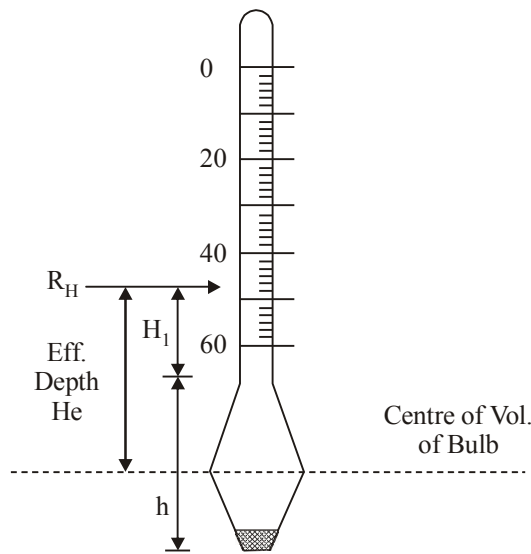
- If M_d = total mass of soil dissolved in total volume of water (V). then mass/unit volume = $\frac{M_d}{V}$

Therefore. % finer is given by $\% N = \frac{\frac{m_d}{V_p}}{\frac{M_d}{V}}$

- If m is the mass of dispersing agent dissolved in the total volume V. then actual % finer.

$$\% N = \frac{\frac{m_d}{V_p} - \frac{m}{V}}{\frac{M_d}{V}}$$

- **Hydrometer Method :** In this method the weight of solids present at any time is calculated indirectly by reading the density of soil suspension.
- Calibration of hydrometer : Establishing a relation between the hydrometer reading R_{11} and effective depth (H_e).
- The effective depth is the distance from the surface of the soil suspension to be the level at which the density of soil suspension is being measured.



- Effective depth is calculated as

$$H_e = H_1 + \frac{1}{2} \left(h - \frac{V_H}{A_j} \right)$$

where,

H_1 = distance (cm) between any hydrometer reading and neck.

h = length of hydrometer bulb

V_H = volume of hydrometer bulb

A_j = area of the cross section of the Jar.

Reading of Hydrometer is related to sp. gr. or density of soil suspension as:

$$G_{ss} = 1 + \frac{R_H}{1000}$$

Thus a reading of $R_H = 25$ means. $G_{ss} = 1.025$ and a reading of $R_H = -25$ means. $G_{ss} = 0.975$

% finer is given as:

$$N = \frac{G}{G-1} \cdot \gamma_w \cdot \frac{V}{W} \cdot \frac{R_H}{10} \%$$

where,

G = Specific gravity of soil solids

R_H = Final corrected value of hydrometer

V = Total volume of soil suspension

W = Weight of soil mass dissolved.

Corrections to Hydrometer Reading

Meniscus Correction: (C_m) : Hydrometer reading is always corresponding to the upper level of meniscus. But it should be taken at lower level, Since hydrometer reading increase down word, Therefore, meniscus correction is always positive ($+C_m$).