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DDA – Junior Engineer

Civil Engineering

Delhi Development Authority (DDA)

Volume - 3

Junior Engineer (Civil)

SOIL Foundation Engineering

SIERRA
INNOVATIONS

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1

CHAPTER

Basic Types of Soil

THEORY

1.1 SOIL TYPES AND FORMATIONS

- There are two main groups of soils according to their origin (i) soils formed by physical weathering e.g., Gravel and Sand (ii) Soils formed by chemical weathering e.g., silts and clays.
- If the products of rock weathering are still located at the place of origin, they are called Residual soils.
- Any soil that has been transported from its place of origin by wind, water, ice or any other agency and has been re-deposited is called Transported soil.
- **Alluvial Soils :** deposited from suspension in Running Water.
- **Lacustrine Soils :** deposited from suspension in still, fresh water of lakes.
- **Marine Soils :** deposited from suspension in sea water.
- **Aeolian Soils :** Transported by wind.
- **Glacial Soils :** Transported by Ice.

1.2 SOME SPECIAL/TYPICAL SOILS

- **Loess :** A loose deposit of windblown silt that has been weakly cemented with calcium carbonate and montmorillonite.
- **Bentonite :** A chemically weathered volcanic ash.
- **Peat:** A highly organic soil; fibrous and highly compressible.
- **Muck :** A mixture of fine particles, inorganic soil and black, decomposed organic mater.

  Note : Peat and Muck are also called cumulose soils.
- **Colluvial Soil :** the accumulation of rock debris or **Talus** at the base of a steep cliff or a rock escarpment due to action of gravity.
- **Marl :** A very fine grained calcium carbonated soil of marine origin.

1.3 Some Common Soils and Engineering Problems Encountered with them

- **Marine Deposits :** Marine clays are very soft and may contain organic matter.
- These Possess low shear strength and high compressibility hence, pose problems as foundation material.
- **Laterites And Lateritic Soils :** Formed by decomposition of rock. removal of the bases and silica and formation of oxides of iron and aluminium at the top of the soil profile.
- These are two types – Primary and Secondary. Primary laterite is found at high altitude near hills.
- Secondary laterites are found at coastal belts.
- Generally laterites pose no difficulties as foundation material and retain their slopes well.
- **Black Cotton Soils :** These soils have been formed from basalt or trap and contain clay mineral montmorillonite, which is responsible for the excessive swelling and shrinkage characteristics of the soil.
- Under reamed piles should be used in foundations in these soils.
- **Desert Soils :** These are wind blown deposits of sand.
- Dune sand is non plastic uniformly graded fine sand.
- Problems associated with these soils are of soil stabilization for roads and runways for reducing settlement under static and dynamic loads and reducing its perviousness to make it suitable for storage and transport of water.

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2
CHAPTER

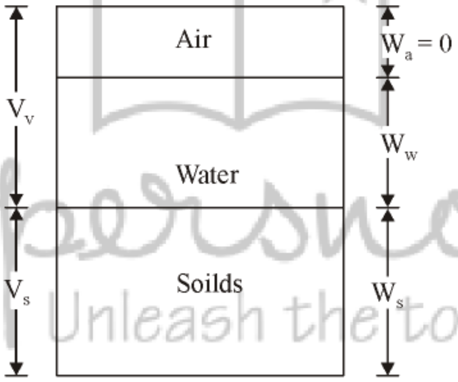
Properties of Soils

THEORY

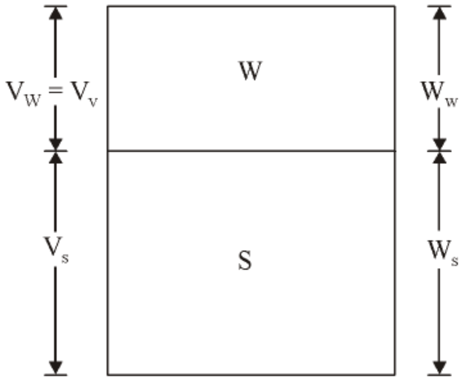
2.1 PROPERTIES OF SOILS

2.1.1 Phase Diagram

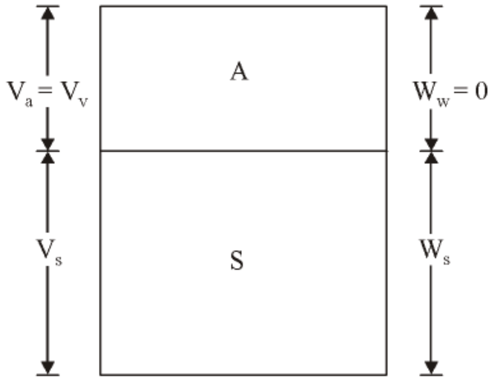
- Soil mass is in general a three phase system composed to solid, liquid and gaseous matter.
- The diagrammatic representation of the different phases in a soil mass is called the "phase diagram."
- A 3-phase system is applicable for partially saturated soil whereas, a 2-phase system is for saturated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

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

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

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

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

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

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

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)

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

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

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

Relation between γ, γ_d and γ_w

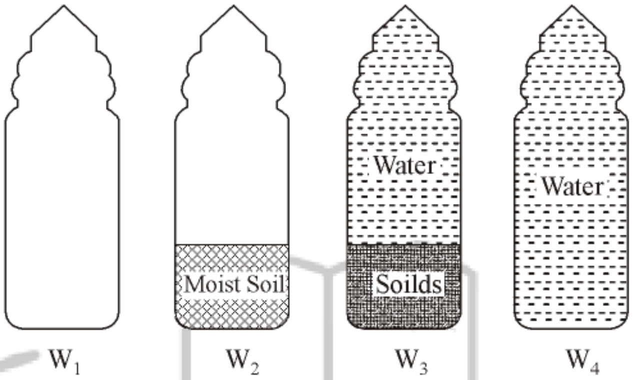
$$\gamma_d = \frac{\gamma}{1+w}$$

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

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

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:

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

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

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

$CaC_2 + 2H_2O \rightarrow C_2H_2 \uparrow + Ca(OH)_2$

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 store.
- Water content is determined by using same formula as in oven drying method.

2.3.5 Torsion Balance Moisture Meter Method

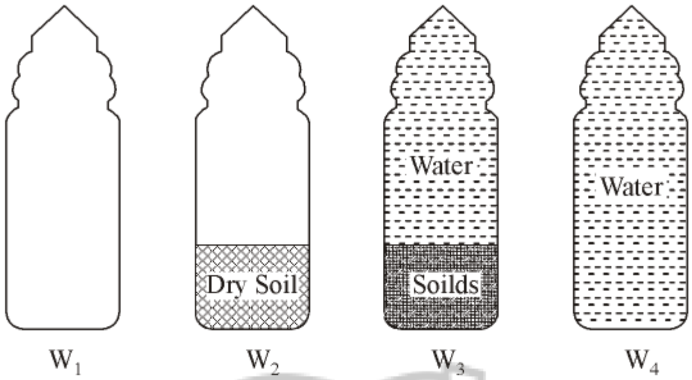
- Quick method for use in laboratory.
- Infrared radiations are used for drying samples.
- **Principle :** The torsion wire is prestressed accurately to an extent equal to 100% of the scale reading. Then the sample is evenly distributed on the balance pan to counteract the prestressed torsion and the 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



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

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

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,

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

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

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

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,

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

where v is in cm/s

and D is in mm.

(ii)

$$V \approx 107\ D^2 \qquad \text{.........at } 27^\circ\ \text{C}$$

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

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

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

- 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., H_2O_2)
- For calcium compounds – Acids are used (e.g., HCI)
- **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 = $\frac{M_d}{V}$

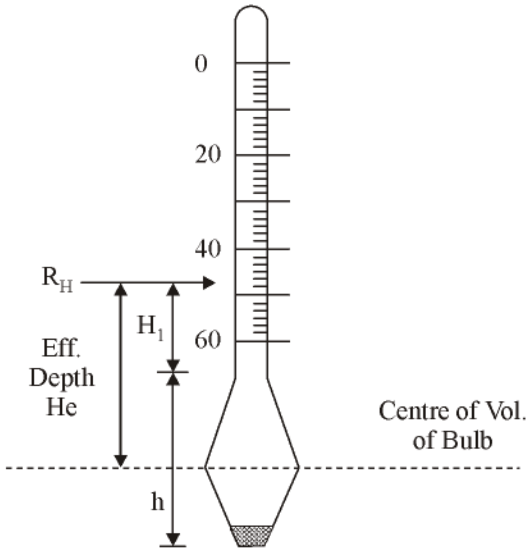
Therefore. % finer is given by $\% \text{ N} = \dfrac{\frac{m_d}{V_p}}{\frac{M_d}{V}}$

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

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

- **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:

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

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 ($+C_m$).

Temperature Correction : (C_t) : Hydrometers are generally calibrated at 27°C. If the test temperature is above the standard (27°C) the correction is added and, if below, it is subtracted.

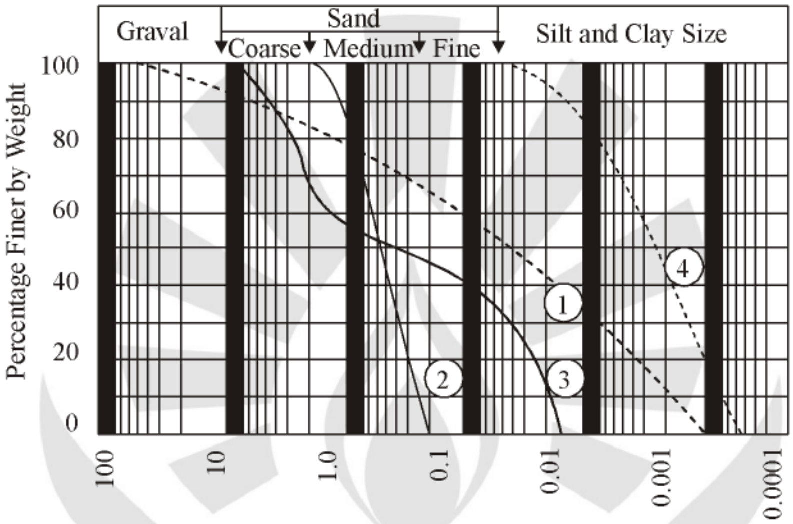
Dispersing/Deflocculating Agent Correction : (C_d) : The correction due to rise in specific gravity of the suspension on account of the addition of the deflocculating agent is called Dispersing agent correction (C_d).

- C_d is always negative.

The corrected hydrometer reading is given by

$$(R_H) = R_H + C_m \pm C_t - C_d$$

2.7 GRAIN SIZE DISTRIBUTION CURVES



Curve 1 : Well graded soil: good representation of grain sizes over a wide range and its gradation curve is smooth.

Curve 2 : Poorly graded soil/Uniform gradation : It is either an excess or a deficiency of certain particle sizes or has most of the particles about the same size.

Curve 3 : Gap graded soil : In this case some of the particle sizes are missing.

Curve 2 : Predominantly coarse soil.

Curve 4 : Predominantly fine soil.

- If slope of the curve is steep, soil is poorly graded.
- If slope is inclined, soil is well graded.
- The diameter D_{10} corresponds to 10% of the sample finer in weight on the Grain size distribution curve.
- This diameter D_{10} is called effective size.
- Similarly D_{30} and D_{60} are grain diameter (mm) corresponding to 30% finer and 60% finer.
- The shape parameters related to these are

(a) Coefficient of Uniformity $\quad C_u = \dfrac{D_{60}}{D_{10}}$

(b) Coefficient of Curvature: $\quad C_c = \dfrac{D_{30}^2}{D_{10} \times D_{60}}$

For a soil to be well graded:

$[1 < C_c < 3]$ and $[Cu > 4]$ for gravels;

$[C_u > 6]$ for sands.

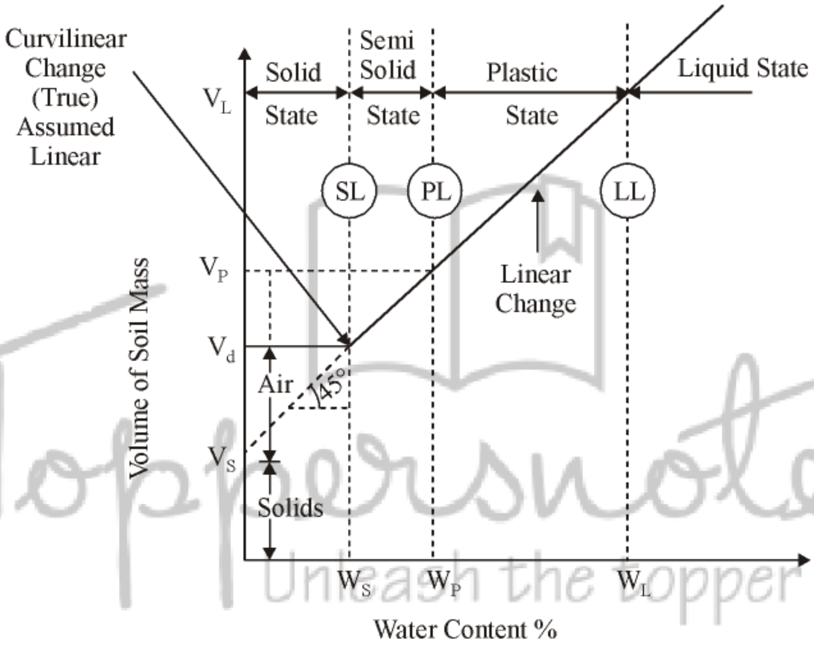
$Cu \approx 1$ for uniform soils/poorly graded soils.

2.8 CONSISTENCY OF CLAYS : ATTERBERG LIMITS

- The relative ease with which a soil can be deformed.
- In practice, consistency is a property associated only with fine grained soils, especially clays.
- Four stages of consistency are used to describe the state of a clayey soil

  (i) The liquid state (ii) The plastic state

  (iii) The semisolid state (iv) The solid state.
- Shrinkage limit is the smallest value of water content at complete saturation of soil mass.



LL = w_L = liquid limit

PL = w_p = Plastic limit

SL = w_s = Shrinkage limit

V_L = Volume of soil mass at LL

V_P = Volume of soil mass at PL

V_d = Volume of soil mass at SL

V_s = Volume of solids.

- The boundary water contents at which the soil undergoes a change from one state to another are called **Consistency limits.** They are also known as Atterberg limits after Swedish scientist Atterberg, who first demonstrated the significance of these limits.
- **Liquid Limit :** The boundary water content between the liquid state and the plastic state is called the liquid limit.

- This is the stage when the sample changes from possessing no shearing strength to having an infinitesimal shear strength.
- **Plastic Limit :** The water content at which soil sample changes from plastic state to semisolid state. (i.e., soil loses its plasticity and behaves like a brittle material when goes to semisolid state).
- **Shrinkage Limit :** A state when a decrease in moisture, leads to no change in volume of soil mass; the sample changes from semisolid to solid state. The boundary water content is called shrinkage limit. (SL)

  Note : SL soil sample is Just fully saturated ($S = 100\%$)
- Liquid limit is also defined as the water content at which a groove cut in a pat of soil by a grooving tool of standard dimensions will flow together for a distance of 13 mm under the impact of 25 blows in a standard liquid limit device.
- Plastic limit is also defined as the water content at which a soil would just begin to crumble when rolled into a thread of approximately 3 mm diameter.

2.9 INDEX PROPERTIES OF SOIL

2.9.1 Plasticity Index (I_P)

- is the range of moisture content over which a soil exhibits plasticity.

$$I_P = w_L - w_P$$

w_L = water content at LL

w_P = water content at PL

- Clay soils possessing high values of liquid limit and plasticity Index are referred to as highly plastic or Fat clays, and those with low values are described as **lean clays**.
- If PL $\geq$ LL I_P is reported as zero.
- Soil classification related to plasticity Index :

I_P (%)	**Soil Description**
0	Non Plastic
1 to 5	Slight Plastic
5 to 10	Low Plastic
10 to 20	Medium Plastic
20 to 40	Highly Plastic
> 40	Very Highly Plastic

2.9.2 Relative Consistency or Consistency-Index (I_c)

- It is defined as a ratio of the difference between the liquid limit and the natural water content of the soil to its plasticity index.

$$I_c = \frac{w_L - w_N}{I_P} \qquad \left.\begin{array}{l} \text{for } w_N = w_L \Rightarrow I_c = 0 \\ \text{for } w_S = w_P \Rightarrow I_c = 1 \end{array}\right\}$$

- If $I_c < 0$, the natural water content of soil (w_N) is greater than w_L and the soil mass behaves like a liquid, but only upon disturbance.
- If $I_c > 1$, soil is in semi solid state and will be very hard or stiff.

2.9.3 Liquidity Index (I_L)

- It is defined as the ratio of the difference between the natural water content of a soil and its plastic limit to its plasticity index.

$$I_L = \frac{w_n - w_P}{I_P}$$

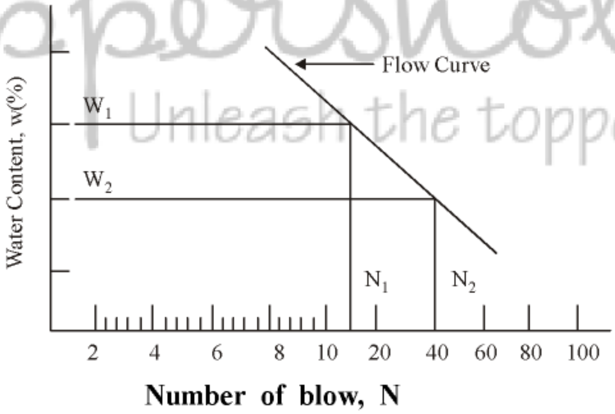
- For a soil in plastic state I_L varies from 0 to 1.

Consistency	**Description**	**I_C**	**I_L**
Liquid	Liquid	< 0	> 1
Plastic	Very Soft	0 – 0.25	0.75 – 1.00
	Soft	0.25 – 0.5	0.50 – 0.75
	Medium Stiff	0.50 – 0.75	0.25 – 0.50
	Stiff	0.75 – 1.00	0.0 – 0.25
Semi-Solid	Very Stiff or Hard	> 1	< 0
Solid	Hard or Very Hard	> 1	< 0

2.9.4 Flow Index (I_f)

- It is the slope of flow curve, obtained between the number of blows and the water content in the A Casagrande test for the determination of liquid limit.

$$I_f = \frac{w_1 - w_2}{\log_m\left(\frac{N_2}{N_1}\right)}$$



- I_f indicates the rate of loss in shearing strength upon increase in water content.
- Soil having higher value of I_f (steeper flow curve) possesses lower shear strength, whereas, a soil having lower value of I_f (flatter flow curve) has higher shear strength.

2.9.5 Toughness Index (I_t)

- It is defined as the ratio of plasticity index to the flow index.

$$I_T = \frac{I_P}{I_F}$$

- I_T gives an idea about the shear strength of a soil at plastic limit. For the same value of plasticity index, two soils exhibit different toughness bases on flow indices.
- For most of the soils : $0 < I_T < 3$
- When $I_T < 1$, the soil is friable (easily crushed) at the plastic limit.
- **Shrinkage Ratio (SR) :** It is defined as the ratio of a given volume change in a soil, expressed as a percentage of the dry volume, to the corresponding change in water content above the shrinkage limit.

$$SR = \frac{\frac{V_1 - V_2}{V_d} \times 100}{w_1 - w_2}$$

Where,

V_1 = volume of soil mass at water content w_1%.

V_2 = volume of soil mass at water content w_2%.

V_d = volume of dry soil mass

Now. at SL. $w_2 = w_s$ and $V_2 = V_d$

$$\therefore \quad SR = \frac{\left(\frac{V_1 - V_d}{V_d} \times 100\right)}{(w_1 - w_s)}$$

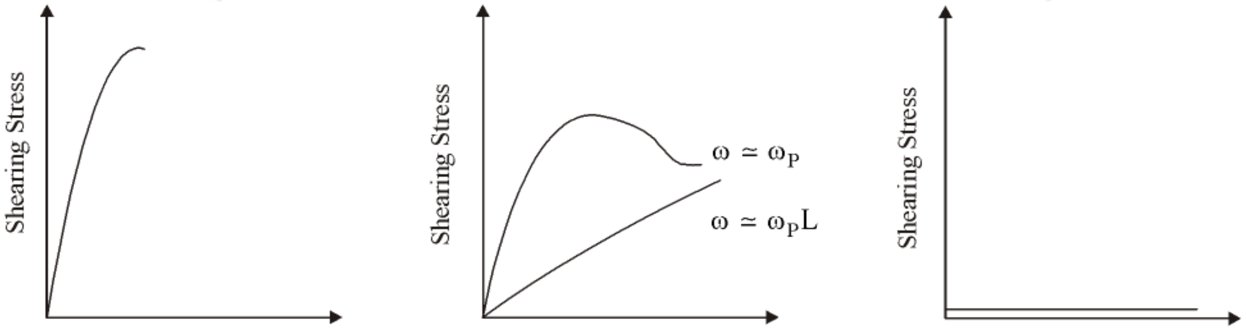
If w_1 and w_2 are expressed as ratio.

$$SR = \frac{\frac{V_1 - V_2}{V_d}}{w_1 - w_2}$$

But $$w_1 - w_2 = \frac{(V_1 - V_2)\gamma_w}{W_s}$$

$$\therefore \quad SR = \frac{W_s}{V_d} \cdot \frac{1}{\gamma_w} = \frac{\gamma_d}{\gamma_w}$$

- **Stress-strain curve for difference consistency states**



(a) $I_L < 0$ (brittle)

(b) $0 < I_L < 1$ (plastic)

(c) $I_L > 1$(liquid)