MODULE- I

INTRODUCTION TO SOIL MECHANICS

Introduction:

Why Geotechnical Engineering?

1. We are unable to build castles in air.
2. Almost every structure is either built on or built in or built using soil or rock.
3. Mechanics of soils and rocks is the basis of Geotechnical engineering.
4. Geotechnical problems involve:
   - Stability
   - Deformations
   - Water flow

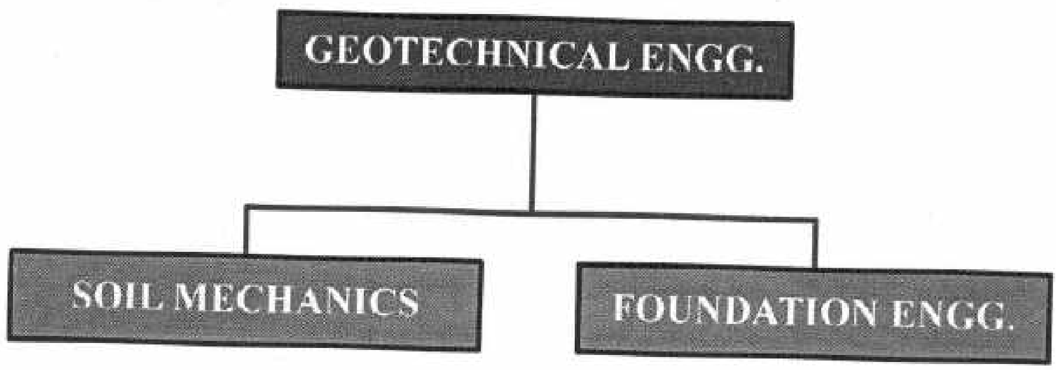
What is Geotechnical Engineering?

Geotechnical Engineering is an integration of Physics, Earth science, Solid mechanics, Geology and Hydrogeology. Soil mechanics provides the theoretical basis for describing the mechanical behavior of earth materials. Geotechnical Engineering involves application of theory of soil mechanics to a variety of field problems. For most other engineering disciplines, the material properties are well defined or can be controlled. But, in Geotechnical Engineering material properties are highly variable and difficult to measure with a reasonable degree of accuracy. Geotechnical Engineering is among the younger braches of Civil Engineering. Yet, it has evolved over centuries.

Geotechnical Engineering is a division of civil engineering concerned with the engineering behavior of earth materials. Geotechnical engineering is a science that explains mechanics of soil and rock. It focused on the analysis, design, and construction of foundations, slopes, retaining structures, embankments, roadways, tunnels, levees, wharves, landfills and other systems that are made of or are supported by soil or rock.

1. Geotechnical Engineering is probably one of the most challenging engineering disciplines.
2. For a geotechnical engineer, no two days at work are going to be similar.
3. Geotechnical Engineering expertise is required in a vast variety of disciplines that includes the oil and offshore industry.

4. Being a relatively new discipline, there is ample scope for innovation.
5. For a geotechincal engineer, achieving job satisfaction is never a problem.
6. Material properties must be measured for each new construction site.
7. Remember that geotechnical engineers deal with natural materials and there can be no quality control.
8. Ground consists of innumerable variety of particle sizes and minerals.
9. To make worse, engineering properties of earth materials are strongly influenced by their past geological history that is normally unknown. Climatic conditions also influence these properties.



Sub braches in Geotechnical Engineering:

The following are the sub branches of Geotechnical Engineering

1. Foundation Engineering
2. Deep excavations
3. Tunneling
4. Earth pressure and retaining structures
5. Earth embankments
6. Stability of slopes
7. Environmental Geotechniques
8. Earthquake Geotechnical engineering
9. Ground improvement technique

10. Rock mechanics
11. Engineering geology

Soil Mechanics: that describes the behavior of soils and determine the relevant physical/mechanical and chemical properties of these soils; soil mechanics provides the theoretical basis for analysis in geotechnical engineering.

Foundation Engineering: is the aspect of engineering concerned with the evaluation of the ability of the earth to support load, and the design of a substructure to transmit the load of the superstructure to the earth.

Soil: is natural mineral particles that can be separated into relatively small pieces and may contain water, air, or organic materials (derived from the decay of vegetation).

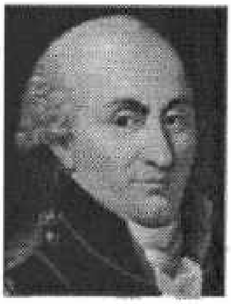
Rock: is a natural material comprised of mineral particles so firmly bonded together that relatively high effort is required to separate the particles (i.e., blasting or heavy crushing forces).

Historical Development of Geotechnical Engineering

Before 18th century: the art of geotechnical engineering was based on only past experiences through a succession of experimentation without any real scientific character. Civilizations such as the Nile (Egypt), the Tigris and Euphrates (Mesopotamia), the Huang Ho (Yellow River, China), and the Indus (India) One of the most famous examples of problems related to soil-bearing capacity in the construction of structures before the 18th century is the Leaning Tower of Pisa in Italy. Construction of the tower began in 1173 A.D.

(1700 –1776) This period concentrated on studies relating to the natural slope and unit weights of various types of soils, as well as the semi-empirical earth pressure theories.

Henri Gautier (1660–1737), Forest de Belidor (1671–1761) (1776 –1856) During this period, most of the developments in the area of geotechnical engineering came from engineers and scientists in France. Practically all theoretical considerations used in calculating lateral earth pressure on retaining walls were based failure surface in the soil.



Charles A. Coulomb (1736-1806) Willian M. Rankine (1820-1872)

(1856 –1910) Several experimental results from laboratory tests on sand appeared in the literature in this period.

• Henri Philibert Gaspard Darcy (1803–1858). Published a study on the permeability of sand filters

• Joseph ValentinBoussinesq (1842–1929), was the development of the theory of stress distribution under loaded bearing areas in a homogeneous.

• Osborne Reynolds (1842–1912) demonstrated the phenomenon of dilation in the sand.

(1910 –1927) In this period, results of research conducted on clays were published in which the fundamental properties and parameters of clay were established.

• Albert MauritzAtterberg (1846–1916), a Swedish chemist and soil scientist, defined clay-size fractions as the percentage by weight of particles smaller than 2 microns in size.

• Karl Terzaghi (1883–1963) developed the theory of consolidation for clay as we know today. In 1925, Terzaghi became recognized as the leader of the new branch of civil engineering called soil mechanics.

1927 – Now

Casagrande – Peck - Bjurrum – Skempton – Tomlinson

Soil Formation

Soil is formed from rock due to erosion and weathering action. Igneous rock is the basic rock formed from the crystallization of molten magma. This rock is formed either inside the earth or on the surface. These rocks undergo metamorphism under high temperature and pressure to form Metamorphic rocks. Both Igneous and metamorphic rocks are converted in to sedimentary rocks due to transportation to different locations by the agencies such as wind, water etc. Finally, near the surface millions of years of erosion and weathering converts rocks in to soil.

In general, soils are formed by weathering of rocks. Rocks can be divided into three basic types: igneous, sedimentary, and metamorphic.

Soils are formed from materials that have resulted from the disintegration of rocks by various processes of physical and chemical weathering. The nature and structure of a given soil depends on the processes and conditions that formed it: □ Breakdown of parent rock: weathering, decomposition, erosion. □ Transportation to site of final deposition: gravity, flowing water, ice, wind. □ Environment of final deposition: flood plain, river terrace, glacial moraine, lacustrine or marine. □ Subsequent conditions of loading and drainage:

little or no surcharge, heavy surcharge due to ice or overlying deposits, change from saline to freshwater, leaching, contamination. All soils originate, directly or indirectly, from different rock types.

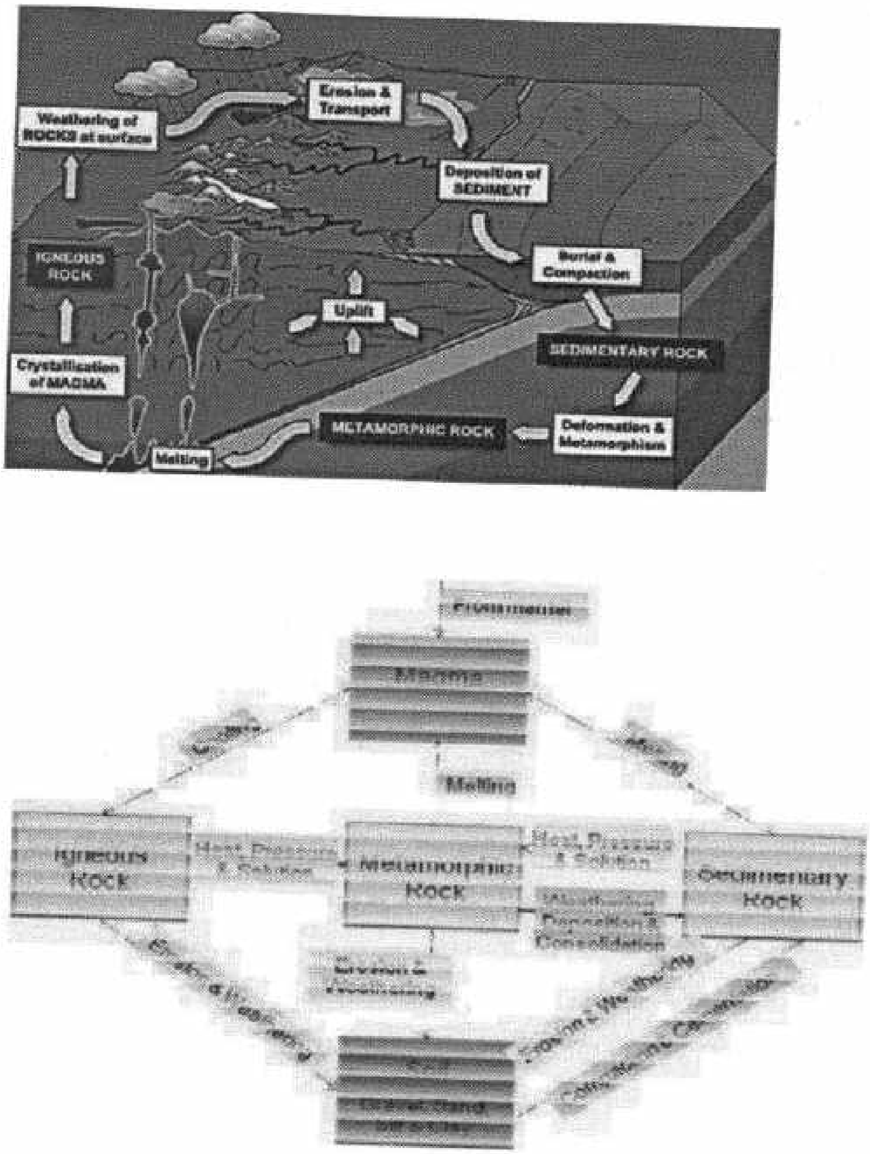


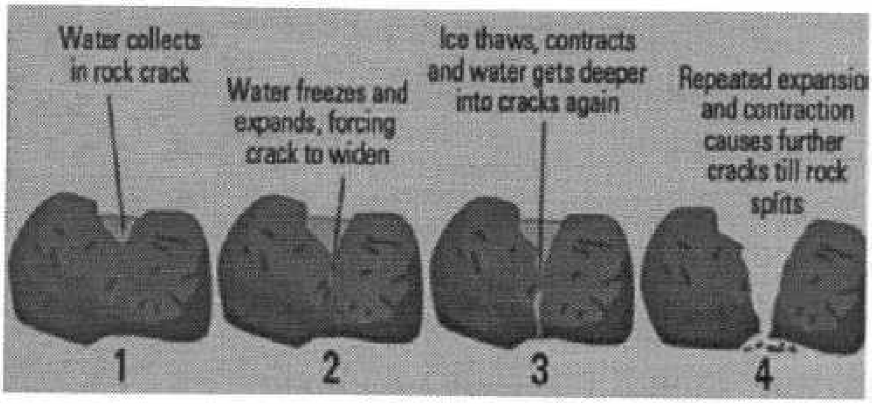
Fig. Geologic Cycle of Soil

Weathering is the process of breaking down rocks by mechanical and chemical processes into smaller pieces. The products of weathering may stay in the same place or may be moved to other places by ice, water, wind, and gravity.

Mechanical weathering may be caused by the expansion and contraction of rocks from the continuous gain and loss of heat. The processes that cause physical weathering are:- •

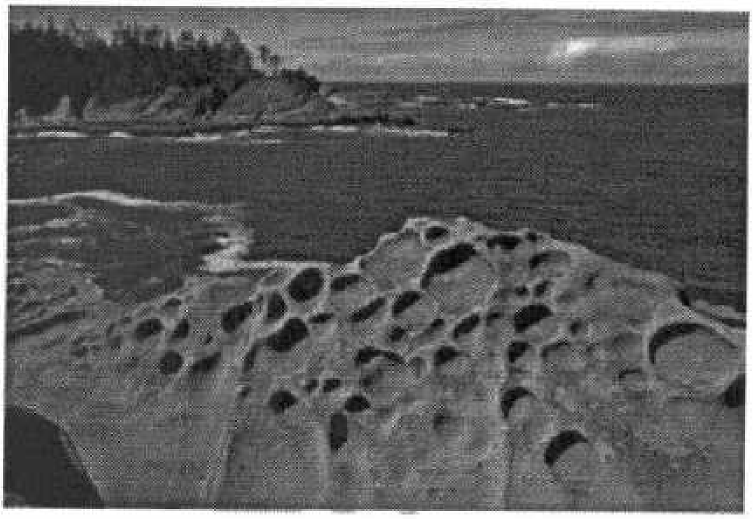
Freezing and thawing • Temperature changes • Erosion (Abrasion) • Activity of plants and animals including man

For example, water seeps into the pores and existing cracks in rocks. As the temperature drops, the water freezes and expands. The pressure exerted by ice because of volume expansion is strong enough to break down even large rocks.



Other physical agents: glacier ice, the wind, running water of streams and rivers, and ocean waves. Its properties are the same as parent rock Chemical weathering, the original rock minerals are transformed into new minerals by chemical reaction.

- Oxidation – union of oxygen with minerals in rocks forming another mineral.
- Hydration – water will enter the crystalline structure of minerals forming another group of minerals.



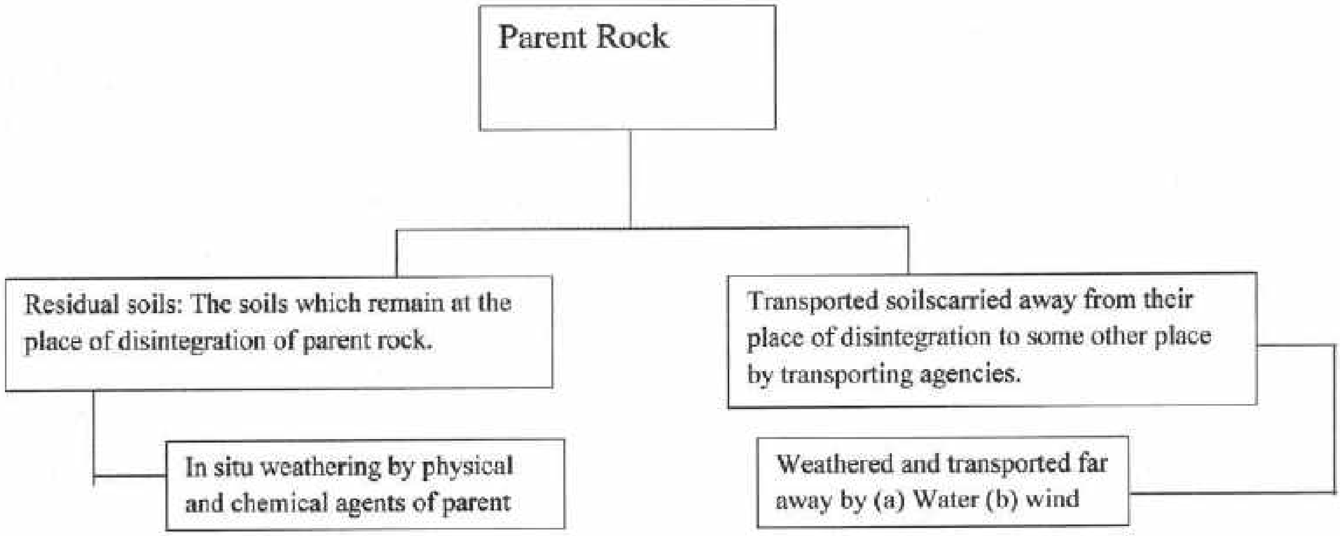
- Hydrolysis – the release Hydrogen from water will union with minerals forming another mineral.

• Carbonation – when CO_2 is available with the existence of water the minerals changed to Carbonates.

The chemical weathering of plagioclase feldspars produces clay minerals, silica, and different soluble salts.

The physical property of this product does not reflect the same properties of the parent rocks.

Depending on the method of deposition, soils can be grouped into two categories:



Soil is an important construction material that is

1. Oldest
2. Cheap or available free of cost many a times.
3. Most complex, yet having interesting properties.
4. Modified to suit the requirements, many a times.

Soil is used

1. To manufacture bricks, Tiles or earthenware.
2. As foundation material.
3. To construct dams and embankments.
4. To fill hollow zones behind retaining walls, low lying areas etc.

Why soil is complex?

The following properties of soil make it perhaps the most complex construction material.

1. Porous
2. Polyphasic
3. Permeable

4. Particulate
5. Heterogeneous
6. Anisotropic
7. Nonlinear
8. Pressure level Dependent
9. Strain level dependent
10. Strain rate dependent
11. Temperature dependent
12. Undergoes volume change in shear

Soil possesses some interesting properties that relate with human beings, they are

1. Colorful
2. Sensitive
3. Possesses memory
4. Changes its properties with time

1. **Residual soils:** the soils formed by the weathered products at their place of origin

Sands: Residual sands and fragments of gravel size formed by solution and leaching of cementing material, leaving the more resistant particles; commonly quartz.

Clays: Residual clays formed by decomposition of silicate rocks, the disintegration of shales, and solution of carbonates in limestone.

2. **Transported soils:**It may be classified into several groups, depending on their mode of transportation and deposition:

Glacial soils—formed by transportation and deposition of glaciers.

Alluvial soils—transported by running water and deposited along streams.

Lacustrine soils—formed by deposition in quiet lakes.

Marine soils—formed by deposition in the seas.

Aeolian soils—transported and deposited by the wind.

Colluvial soils—formed by movement of soil from its original place by gravity, such as during landslides

3. **Organic Soils:** Accumulation of highly organic material formed in place by the growth and subsequent decay of plant life.

Peat: A somewhat fibrous aggregate of decayed and decaying vegetation matter having a dark color

Muck: Peat deposits which have advanced in the stage of decomposition to such extent that the botanical character is no longer evident. Very compressible, entirely unsuitable for supporting building foundations.

Distinctions between fine and coarse grained soils

Soil can be broadly classified into two types, namely Fine grained soil and coarse grained soil based on the size, shape and behavior.

Distinctions between Fine grained soil and coarse grained soil

Fine grained soil	Coarse grained soil
Size of particle is less than 75 microns	Size of particle is more than 75 microns
Silt and clay belong to this group	Sand, gravel, cobble etc. belong to this group
Properties are influenced by surface area	Properties are influenced by gravity
Attraction and bonding between particles enable strength	Dense packing, particle to particle contact enable strength
Mostly plate like	Most round, sub-round, angular
Void ratio and water content can be very high	Void ratio and water content cannot be very high
Possess consistency limits	Consistency limits are absent

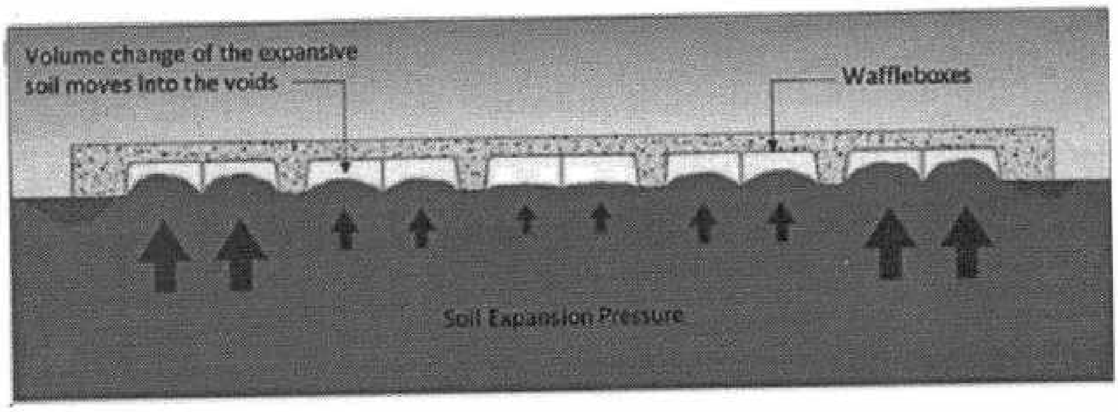
Soil Problems in Civil Engineering:

The soil in civil engineering is used as a foundation material or construction material

Themain purpose of the studying geotechnical engineering is to find the shear strength and settlement of the soil.

Problematic soils

Expansive Soils Expansive soils are distinguished by their potential for great volume increase upon access to moisture. Soils exhibiting such behavior are mostly clays.



Collapsing Soils: Collapsing soils are distinguished by their potential to undergo a large decrease in volume upon an increase in moisture content even without an increase in external loads.

A Preview of Soil Behavior:

The soil is the particulate system. These particles make soil are not strongly bonded together like metal, and the soil particles are free to move on one another, but cannot move relative to each other as easily as an element in the fluid. Soil mechanics distinguished from solid mechanics and fluid mechanics that treats the stress-strain behavior.

The term 'Soil' has different meanings in different scientific fields. It has originated from the Latin word "*Solum*".

To an agricultural scientist, it means "the loose material on the earth' crust consisting of disintegrated rock with an admixture of organic matter, which supports plant life".
To a geologist, it means the disintegrated rock material which has not been transported from the place of origin.

To a pedologist, it is the substance existing on the surface, which supports plant life.
To an engineer, it is a material that can be:

- built on: foundations of buildings, bridges
- built in: basements, culverts, tunnels
- built with: embankments, roads, dams
- supported: retaining walls

Soil Mechanics is a discipline of Civil Engineering involving the study of soil, its behaviour and application as an engineering material.
Soil Mechanics is the application of laws of mechanics and hydraulics to engineering problems dealing with sediments and other unconsolidated accumulations of solid particles, which are produced by the mechanical and chemical disintegration of rocks, regardless of whether or not they contain an admixture of organic constituents.
Soil consists of a multiphase aggregation of solid particles, water, and air. This fundamental composition gives rise to unique engineering properties, and the description of its mechanical behavior requires some of the most classic principles of engineering mechanics.
Engineers are concerned with soil's mechanical properties: permeability, stiffness, and strength. These depend depend primarily on the nature of the soil grains, the current stress, the water content and unit weight.

SOME COMMONLY USED SOIL DESIGNATIONS:

The following are some commonly used soil designations, their definitions and basic properties ***Bentonite:*** Decomposed volcanic ash containing a high percentage of clay mineral montmorillonite. It exhibits high degree of shrinkage and swelling.

Black cotton soil. Black soil containing a high percentage of montmorillonite and colloidal material: exhibits high degree of shrinkage and swelling. The name is derived from the fact that cotton grows well in the black soil.

Boulder cla: Glacial clay containing all sizes of rock fragments from boulders down to finely pulverized clay materials. It is also known as 'Glacial till'.

Calich: Soil conglomerate of gravel, sand and clay cemented by calcium carbonate.

Hard pan: Densely cemented soil which remains hard when wet. Boulder clays or glacial tills may also be called hard-pan- very difficult to penetrate or excavate.

Laterite: Deep brown soil of cellular structure, easy to excavate but gets hardened on exposure to air owing to the formation of hydrated iron oxides.

Loam: Mixture of sand, silt and clay size particles approximately in equal proportions; sometimes contains organic matter. *Loess.* Uniform wind-blown yellowish brown silt or silty clay; exhibits cohesion in the dry condition, which is lost on wetting. Near vertical cuts can be made in the dry condition.

Marl: Mixtures of clacareous sands or clays or loam; clay content not more than 75% and lime content not less than 15%.

Moorum: Gravel mixed with red clay.

Top-soil: Surface material which supports plant life.

Varved clay: Clay and silt of glacial origin, essentially a lacustrine deposit; *varve* is a term of Swedish origin meaning thin layer. Thicker silt varves of summer alternate with thinner clay varves of winter.

MAJOR SOIL DEPOSITS OF INDIA:

The soil deposits of India can be broadly classified into the following five types:

1. **Black cotton soils,** occurring in Maharashtra, Gujarat, Madhya Pradesh, Karnataka, parts of Andhra Pradesh and Tamil Nadu. These are expansive in nature. On account of Fig.Flocculent structure flaky particles and Dispersed structure high swelling and shrinkage potential these are difficult soils to deal with in foundation design.

2. **Marine soils,** occurring in a narrow belt all along the coast, especially in the Rann of Kutch. These are very soft and sometimes contain organic matter, possess low strength and high compressibility.

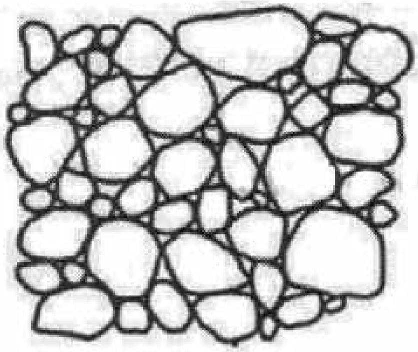
3. **Desert soils,** occurring in Rajasthan. These are deposited by wind and are uniformly graded.

4. **Alluvial soils,** occurring in the Indo-Gangetic plain, north of the Vindhyachal ranges.

5. Lateritic soils, occurring in Kerala, South Maharashtra, Karnataka, Orissa and West Bengal.

Phase relations of soils:

Soil is an un-cemented aggregate of mineral grains and decayed organic matter (solid particles) with liquid and gas in the empty space between the solid particles formed by weathering of rocks in the top surface of earth crust. The figure represents a portion of a soil mass comprising soild particles and void space. Void space is made up of liquid(water) and/ gas (air).



Soil mass, a conglomeration of solid particles and void space

Soil is not a coherent solid material like steel and concrete, but is particulate material. Soils, as they exist in nature, consist of solid particles (mineral grains, rock fragments) with and air in the voids between the particles. The water and air contents are readily changed by changes in ambient conditions and locations.

As the relative proportions of the three phases vary in any soil deposit, it is useful to consider a soil model which will represent these phases distinctly and properly quantify the amount of each phase. A schematic diagram of the three phase system is shown in terms of weight and volume symbols respectively for solids, water and air. The weight of air can be neglected.

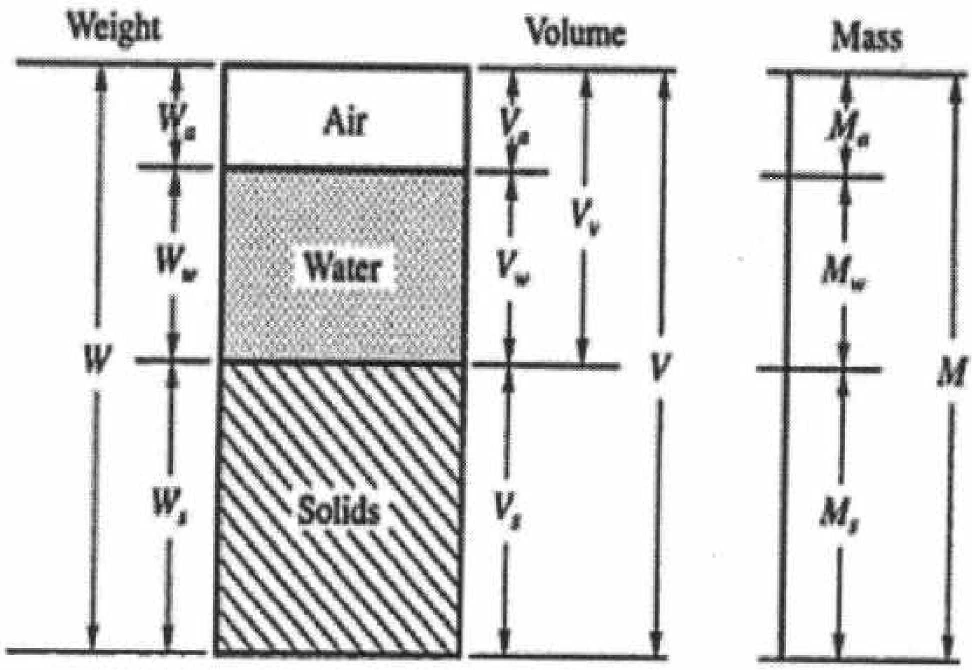


Figure : Block diagram- three phases of a soil element

The soil model is given dimensional values for the solid, water and air components.

Total volume $V = V_s + V_w + V_v$

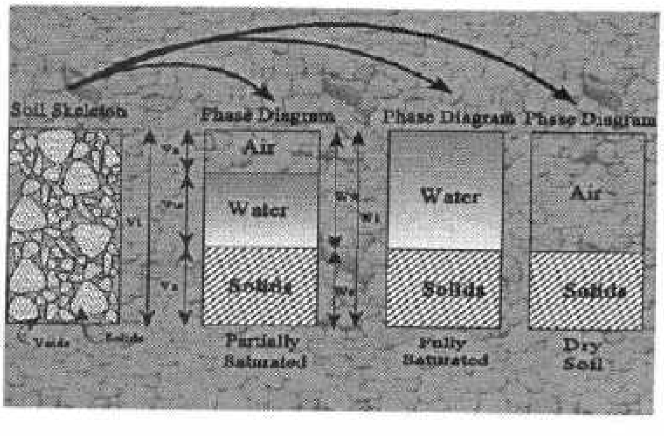
Weight

W = Ws + Ww + Wg

Three -phase system:

Soils can be partially saturated(with both air and water present).or be fully saturated(no air content) or be perfectly dry(no water content).

In a saturated or a dry soil, the three phase system thus reduces to two phases only, as shown



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.

1. Volumetric Relationships

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

i) Void ratio (e) :

It is defined as the ratio of volume of voids to the volume of solids.

$\mathbf{e} = \frac{V_v}{V_s}$; the void ratio is expressed in decimal. where V_v = Volume of voids, V_s = Volume of soil solids

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

ii) Porosity (n) or Percentage of voids

It is defined as the ratio of the volume of voids to the total volume.

In porosity total volume of soil is used which includes volume of voids.

$n = \frac{V_v}{V}$; Porosity is expressed as percentage & it is not exceed 100%.

The range of porosity is 0 < n < 100%.

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

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

iii) Degree of Saturation (S)

The degree of saturation (s) is the ratio of the volume of water to the volume ofvoids.

$\mathbf{S} = \frac{V_w}{V_v}$; The degree of saturation is generally as a percentage . It is equal to zero when the soil is absolutely dry & 100 % when the soil is fully saturated. Where as partially saturated soil have 0 < S < 100%.

iv) Percentage of air voids (n_a)

It is defined a s the ratio of the volume of air to the total v olum, .$\mathbf{n_a} = \frac{V_a}{V}$ (it is represented as(%)

v) Air Content (ac)

It is defined as the ratio of the volume of air to the volume of voids, $a_c = \frac{V_a}{V_v}$,

Air Content is usually expressed as percentage. Air Content and percentage of air voids are zero when the soil is saturated.(V_a=0)

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

$$\mathbf{n_a = n.a_c}$$

vi) Water content (w)

The water content (w) is defined as the ratio of the mass of water to mass of solids.

$\mathbf{w} = \frac{M_w}{M_s}$. It is also known as moisture content (m); it is expressed as percentage but used as a decimal computation.

2. Volume Mass Relationships

i) Bulk density (ρ)

The bulk mass density (ρ) is defined as the total mass (M) per unit total volume (V)

$\rho = \frac{M}{V}$. It is also known as Bulk mass density, Bulk density, Wet mass density and density.

It is expressed as kg/m^3, gm/ml (or) mg/m^3

ii) Dry mass density (ρ_d)

The dry density (?d) is defined as the mass of solids per unit total volume.

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

iii)Saturated density(ρ_{sat})

Saturated density the bulk mass density of the soil when it is fully saturated.

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

iv)Submerged density(ρ')

When the soil exists below water it is submerged conditions. When a volume of v of soil is submerged in water, it displaces an equal volume of water.

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

v)Density of soil solids

Density of solids is equal to the ratio of the mass of solids to the volume of solids.

$$\rho s = \frac{M_s}{V_s}$$

3. Volume-Weight Relationships

i)Bulk unit weight (γ)

Bulk unit weight is defined as total weight per unit total volume.

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

ii) Dry unit weight (γ_d)

It is defined as the weight of soil solids per unit total volume. $\gamma_d = \frac{W_s}{V}$

iii) Saturated unit weight

The saturated unit weight is bulk unit weight when the soil is fully saturated. It is defined as weight of saturated soil solids to the unit total volume. $\gamma_{sat} = \frac{W_{sat}}{V}$

iv) Submerged unit weight (γ')

It is defined as the submerged weight per unit of total volume.

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

$$\gamma' = \gamma_{sat} - \gamma_w$$

v) Unit weight of soil solids (γs)

The unit weight of solids (γs) is equal to the ratio of the weight of solids to the total volume of solids. $\gamma s = \frac{W_s}{V_s}$

4 Specific gravity of solids (G)

i) The specific gravity of solid particles is defined as the ratio of the mass of a given volume of solids to the mass of an equal volume of water @ 4°C. $G = \frac{\rho_s}{\rho_w} = \frac{\gamma_s}{\gamma_w}$

The specific gravity of solids for most natural soils is range of 2.65 to 2.80.

ii) Mass specific gravity (or) apparent specific gravity (or) Bulk specific gravity

It is defined as the ratio of the mass density of the soil to the mass density of water.

$G_m = \frac{\rho}{\rho_w} = \frac{\gamma}{\gamma_w}$

iii) Absolute specific gravity (or) True specific gravity

If all the internal voids of the particles are exclude from the determination the true volume of solids, then the specific gravity is called as Absolute (or) True specific gravity.

$G_a = \frac{\rho_s}{\rho_w}$

Basic Definitions

Water Content (w) / moisture content

It is the ratio of weight of water to the weight of soil solids. $w = \frac{W_w}{W_s}$; $w \geq 0$

- This is 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%.

Note:- 1. Fine grained soils have higher values of natural moisture content as compared to coarse grained soils.

2. There are four possible forms of water present in soil.

(i) Gravity water (free water) Added due to rain or flooding.

(ii) Capillary water: Extracted through capillary action

(iii) Hygroscopic water: water absorbed by oven dried sample when it is placed in open atmosphere.

(iv) Structural water:- water bounded in crystalline structure of soil.

On ovendrying gravity water, capillary water, and hygroscopic water are removed but structural water remains present in soil mass.

3. Water content in soil represents gravity water, capillary water and hygroscopic water which can be removed on ovendrying.

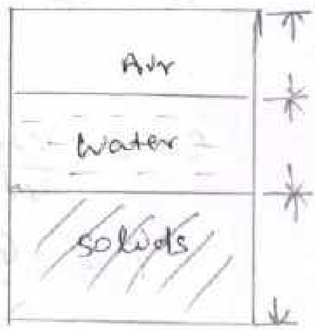
Degree of Saturation (S)

Note:- 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 further addition of water then volume of void and total volume increases. Hence void ratio will change but degree of saturation remains constant equal to 100%.

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

FUNCTIONAL RELATIONSHIPS

Relation between e and n



we know $e = \frac{V_v}{V_s}$, $n = \frac{V_v}{V}$

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

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

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

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

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

Relation between a_c and n_a

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

$$n_a = \frac{V_a}{V} = \frac{V_a}{V_v} \times \frac{V_v}{V} \Rightarrow \boxed{n_a = n a_c}$$

Since $V_a = V_v - V_w$

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

Relation between W_s, W & w

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

W = Total wt. of soil mass

W_s = wt. of solids

w = water content

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

Relation between e, w, G, S

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

$$= \frac{V_v}{V_w} \times \frac{W_w / \gamma_w}{W_s / \gamma_s} = \frac{V_v}{V_w} \times \frac{W_w}{W_s} \times \frac{G\gamma_w}{\gamma_w}$$

$$= \frac{1}{S} wG$$

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

For Fully saturated $S = 1$ $\boxed{e = wG_s}$

Relationship between γ, G, e, w, γ_w

$$\gamma_t = \gamma = \frac{W}{V} = \frac{W_s + W_w}{V_s + V_v} = \frac{W_s\,(1 + W_w/W_s)}{V_s\,(1 + V_v/V_s)}$$

Since $\frac{W_w}{W_s} = w$, $\frac{V_v}{V_s} = e$ & $\frac{W_s}{V_s} = \gamma_s = G\gamma_w$

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

since $w = \frac{Se}{G}$

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

when $S = 0$ soil dry

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

Relationship between γ_{sat}, G, e, γ_w

For a saturated soil in which only solids & water are present

$$\gamma_{sat} = \frac{W}{V} = \frac{W_s + W_w}{V_s + V_v} = \frac{G\gamma_w + e\gamma_w}{1+e}$$

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

Relationship between γ_d, G, e, γ_w

Dry soil only solids & air are present

$$\gamma_d = \frac{W}{V} = \frac{W_s}{V} = \frac{W_s}{V_s + V_v}$$

$$\boxed{\gamma_d = \frac{G\gamma_w}{1+e}} \qquad \text{or } e = \frac{G\gamma_w}{\gamma_d} - 1$$

putting value of $e = \frac{wG}{S}$ in the above eqn

$$\gamma_d = \frac{G\gamma_w}{1 + \frac{wG}{S}}$$

For fully saturated $S = 1$ $\boxed{\gamma_d = \frac{G\gamma_w}{1 + wG}}$

Relationship between γ', γ_w, G, e

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

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

Relation between γ, γ_d, w

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

$$= \gamma_d (1+w) \Rightarrow \boxed{\gamma_d = \frac{\gamma}{1+w}}$$

Relation between γ_d, G, w & n_a

$$V = V_s + V_w + V_a$$

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

$$1 - n_a = \frac{V_s}{V} + \frac{V_w}{V} = \frac{W_s/G\gamma_w}{V} + \frac{W_w/\gamma_w}{V}$$

$$= \frac{\gamma_d}{G\gamma_w} + \frac{w W_s/\gamma_w}{V}$$

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

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

Relationship in mass density

1. $n = \frac{e}{1+e}$
2. $e = \frac{n}{1-n}$
3. $n_a = n a_c$
4. $\rho = \frac{(G + Se)\rho_w}{1+e}$
5. $\rho_d = \frac{G\rho_w}{1+e}$
6. $\rho_{sat} = \left(\frac{G+e}{1+e}\right)\rho_w$
7. $\rho' = \left(\frac{G-1}{1+e}\right)\rho_w$
8. $e = \frac{wG}{S}$
9. $\rho_d = \frac{(1-n_a)G\rho_w}{1+wG}$
10. $\rho_d = \rho/(1+w)$

In unit weight

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

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

$n_a = n a_c$

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

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

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

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

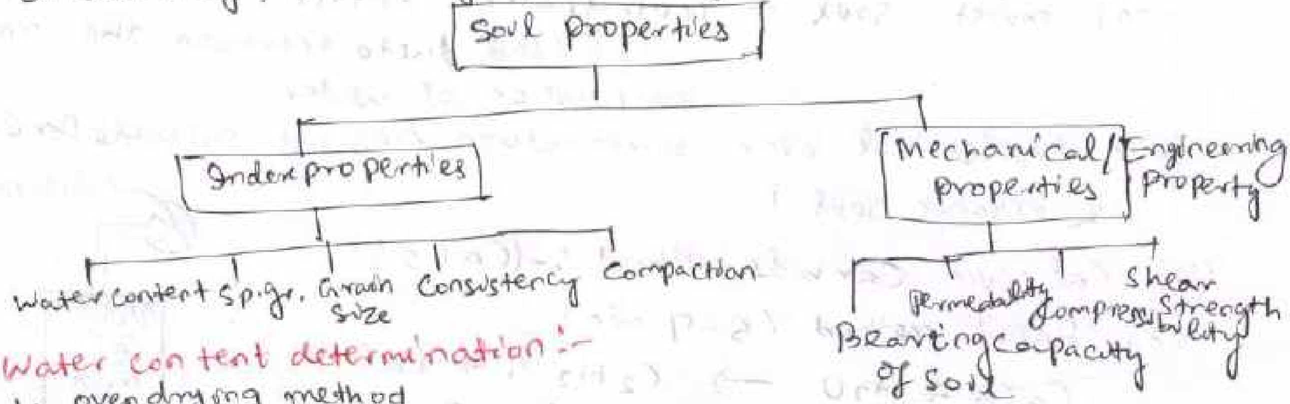
$e = \frac{wG}{S}$

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

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

Index Properties of Soil

Index properties of soil are those which helps in classification and identification of soils. Index properties like water content, sp. gravity, unit weight, particle size distribution, consistency, sensitivity, Thixotropy and Activity



Water content determination :-

1. oven drying method
2. Pycnometer method
3. Torsion Balance method
4. Sand bath method
5. Alcohol method
6. Calcium carbide method
7. Radiation method

Water Content :-

Methods of determination :-

① Oven drying method :-

(a) Most accurate method
(b) Lab. method
(c) In this method moist sample of soil placed in empty container of known weight 'w_1' and again weighted 'w_2'
(d) Then container containing moist sample is placed in temp. controlled oven.
(e) for inorganic soil temperature in oven maintained at 105 - 110°c Sandy soil drying duration - 4 hrs to 6 hrs
silt & clay drying duration - 12 to 16 hrs
(f) Generally 24 hrs of drying duration for all types of soil
(g) For organic soil temp. - 60°c (Because to avoid oxidation of organic matter of soil)
(h) For soil having Gypsum ($CuSO_4 \cdot 2H_2O$ - crystaline water) drying duration limited to 80°c to avoid the loss of water of crystalization.

Temperature never more than 110°c

(2) Sand bath method :-

(i) Field method } when the facility of an electric oven is not available $w = \frac{W_w}{W_s} \times 100\%$

(ii) Quick method }

(iii) Not suitable for Gypsum & organic soil (Due to uncontrolled temperature). wet soil sample is put in a container and dried by placing it on a sand bath. The sand bath is heated over a kerosene stove. The wet soil sample dries quickly

(3) Alcohol method :-

(i) moist soil + methylated spirit
↳ Added due to increase the rate of evaporation of water

(ii) No Control over temperature (So not suitable for Gypsum & organic soil)

(4) Calcium Carbide method :- (CaC_2)

(i) Rapid method (5-7 min)

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

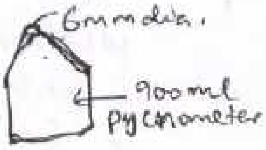
(5) Radiation method :-

(i) Field method
(ii) In this method Radioactive material Cobalt-60 is used

(6) Torsional balance method

(7) Pycnometer method -

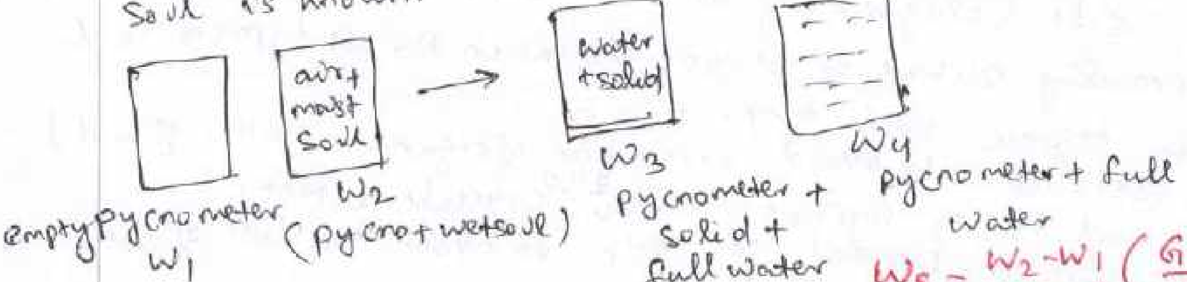
(i) Pycnometer is 900ml flask having conical brass top with 6mm dia circular hole at its centre.



(10-20 min.)

(ii) Also quickest method

(iii) This method is used only when sp. gravity of soil is known.



$$W_s = \frac{W_2 - W_1}{W_3 - W_4}\left(\frac{G-1}{G}\right) - 1$$

Methods of determination of Water Content

1. Oven drying method

- This is the simplest and most accurate method
- For inorganic soils temperature is controlled between 105°-110°C
- For soils containing organic compounds, temperature is maintained about 60°C and if Gypsum is present then temperature should be maintained at 80°C
- Usually 4-6 hrs are enough for sands to dry but 16-20 hrs are required for clay. Usually 24 hrs are provided for drying in the oven.
- 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 = wt. of empty container

W_2 = wt of container + moist soil

W_3 = wt. of container + dry soil

$W_w = W_2 - W_3$

$W_s = W_3 - W_1$

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

This method is accurate but time taking

2. Pycnometer method

- This is a quick method but it is less accurate than oven drying method
- This method is used only when sp. gr. of soil solids is known
- A small weight say 200 to 400g of soil is placed in a clean pycnometer whose capacity is 900ml

Let W_1 = wt. of empty pycnometer bottle

W_2 = wt. of pycnometer + soil

W_3 = wt. of pycnometer + soil + water

W_4 = wt. of pycnometer + water

Let G be sp. gr. of soil solids

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

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

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

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

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

from (i) & (ii) $\left[\because V_s = \frac{W_s}{\gamma_s} \text{ and } G = \frac{\gamma_s}{\gamma_w} \right]$

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

- 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.

- This method is suitable for coarse grained soil.

- Pycnometer method is used for fine grained soil then instead of water kerosene should be used because kerosene has good wetting properties.

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 corelated 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 wt. of soil. Where as 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 $w = \frac{W_r}{1+W_r} \times 100\%$.

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.
- Water content is determined similar to oven drying method $w = \frac{W_2 - W_3}{W_3 - W_1} \times 100$

W_1 = wt. of empty container

W_2 = wt. of container + moist soil

W_3 = wt. of container + dry soil

Since temperature is uncontrolled hence there is a change of loss of structural water.

5. Alcohol method —

- It is also a quick method adopted in field
- In this method methylated sprit is mixed with the soil sample in order to increase the rate of evaporation and then methylated spirit is ignited

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

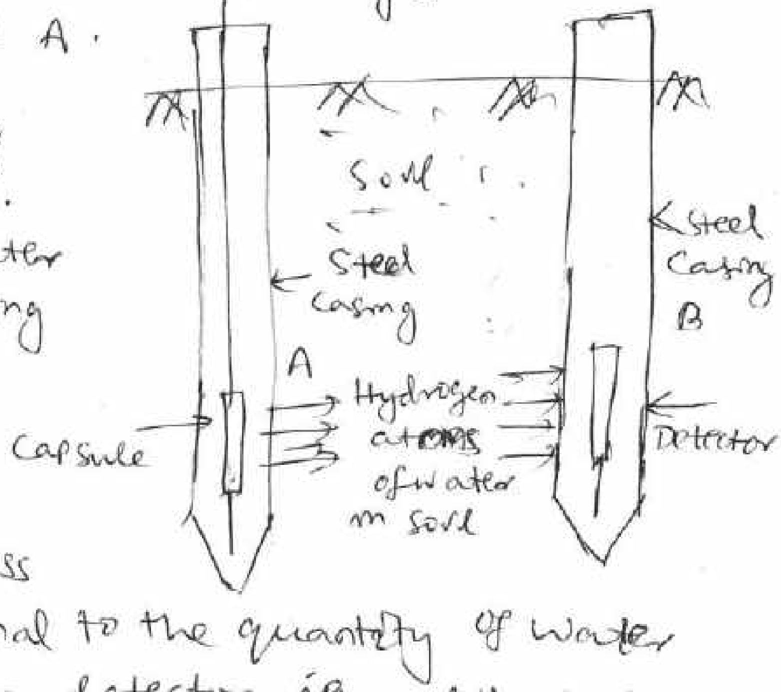
Where W_1 = wt of sample

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

This method is very rapid but less accurate

6. Torsion Balance method
- It is a laboratory method
- In this method, infrared radiation is used for drying soil sample
- In this method drying & weighing are done simultaneously
- This method is rapid, accurate and most suitable for soils which quickly reabsorb moisture after drying

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. 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 has a opening facing that of A.

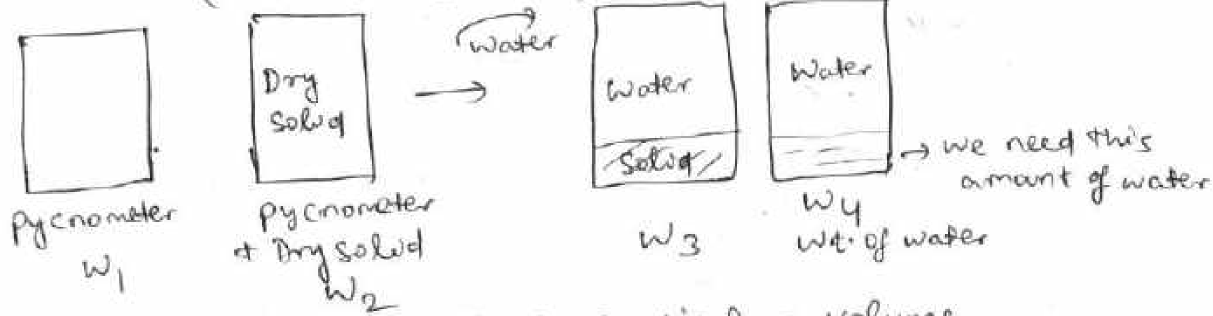


- Neutrons are emitted by the radioactive material. The Hydrogen atoms in water of the soil cause scattering of neutrons. As these neutrons strike with the hydrogen atom, they lose energy. The loss of energy is proportional to the quantity of water present in the soil. The detector is calibrated to give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

Specific Gravity :-

Methods for determination

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



$$\text{specific gravity} = \frac{\text{wt. of particular volume}}{\text{wt. of standard fluid of same volume as material}}$$

(Standard fluid = water)

Specific gravity is of two types

1. G_s = True specific gravity | Absolute sp. gravity
2. G_m = Mass specific gravity | Apparent sp. gravity

$$G_s = \frac{\text{wt. of solid}}{\text{wt. of standard fluid of same volume as solid}}$$

$$G_m = \frac{\text{wt. of total soil}}{\text{wt. of standard fluid of same volume as soil}}$$

[Note:- Consistency - Related to flow
Degree of firmness Related to strength (DF)]

$$\left(\text{Consistency} \propto \frac{1}{DF}\right)$$

Note: Density bottle method is suitable for fine grained soils with more than 90% passing 2mm IS sieve. This method can be used for medium & coarse grained soils if they are pulverised such that the particles pass 2mm IS sieve.
The pycnometer method can be used for all types of soils but is more suitable for medium grained soils with more than 90% passing a 20mm IS sieve & for coarse grained soils with more than 90% passing a 40mm IS sieve

$$\boxed{G_s = \frac{W_s}{W_s - (W_3 - W_4)}}$$

If kerosene is used

$$G_s = \frac{W_s G_k}{W_s - (W_3 - W_4)} \qquad G_k = \text{sp. gr. of kerosene}$$

Density Index / Relative Density / Degree of density (I_D)

Relative density indicates the degree of compactness of soil.

$$I_D = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100$$

e = void ratio of soil at its natural state

e_{max} = the void ratio of soil is maximum when it is in loose state

e_{min} = the void ratio of the soil is minimum when the soil is in densest state

Loose state (e_{max}) Dense state (e_{min})

I_D is used for cohesionless soil only

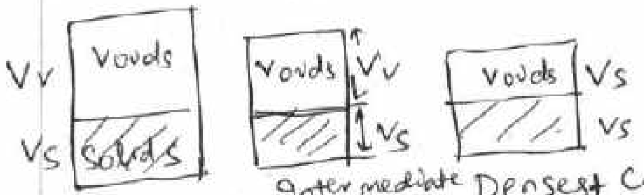
$e = e_{max}$ $I_D = 0$ Intermediate state I_D between 0 & 1

$e = e_{min}$ $I_D = 1$

Relative Density I_D (%)	Descriptive Condition	Typical range of unit weight
0 - 15	very loose	< 14
15 - 35	loose	14-17
35 - 65	Medium	17 to 20
65 - 85	Dense	Above 20
85 - 100	very dense	

Note: In dense condition the void ratio is low, in loose condition the void ratio is high.

The in place in situ void ratio may be determined & compared with the void ratio in the loosest state & that in densest state.



Loose state e_{max} Intermediate State Densest Condition e_{min}

$$I_D = \left(\frac{1}{\gamma_{min}} - \frac{1}{\gamma_d}\right) \Big/ \left(\frac{1}{\gamma_{min}} - \frac{1}{\gamma_{max}}\right)$$

$$= \frac{\gamma_{max}}{\gamma_d}\left(\frac{\gamma_d - \gamma_{min}}{\gamma_{max} - \gamma_{min}}\right)$$

Water content determination

procedure:

- A clean non corridable container which is weighed accurately to 0.01g
- About 30-40g of moist sample is taken & weighed accurately after being placed in the container
- The container which the sample is kept in the oven and taken out after 24hrs and weighed again.

w_1 = wt. of empty container

w_2 = wt. of container + moist soil sample

w_3 = wt. of dried sample

$$w = \frac{W_w}{W_s} \times 100 \Rightarrow w = \frac{(w_2 - w_3)}{(w_3 - w_1)} \times 100$$

Specific gravity determination

- It is used for computation of several quantities such as void ratio, degree of saturation, unit wt. of solids and unit wt. of soil in various states
- It's determined by pycnometer & sp.gr. bottle.

Procedure:-

- weigh empty dry pycnometer bottle w_1
- 300gm of oven dried sample placed in pycnometer and weighed w_2.
- pycnometer + soil + water is filled and closed and air entraped in soil is removed by stirring with glass rod (w_3)
- pycnometer + full water weighed w_4
- wt. of dry soil w_s as $w_2 - w_1$
- wt. of water having the same volume as that of solids
$= (w_2 - w_1) - (w_3 - w_4)$

$$\text{Sp. gravity} = \frac{(w_2 - w_1)}{(w_2 - w_1) - (w_3 - w_4)}$$

G values are usually reported at 27°C

If T°C is the test temperature the sp. gr. at 27°C is given by

$$G_{(27°C)} = G_{(T°C)} \times \frac{\text{sp. gr. of water at } T°C}{\text{sp. gr. of water at } 27°C}$$

Soil sample to be taken should pass through 4.75 mm sieve.

- suitable preferably cohesionless soil

Sieve Analysis

procedure : (1) A suitable quantity of dry and pulverised soil of known weight (about 500gm) is taken and is sieved for a selected set of sieves arranged according to their sizes.

2. Largest sieve at top and smallest at bottom with a pan receiver at the bottom most end.

3. The top sieve is closed by a lid and the whole set up is shaken for about 10 min using mechanical sieve shaker are manual.

- Now the amount of soil retained on each sieve is weighed to the nearest of 0.1g

- on the basis of the total weight of sample taken and the wt. of soil retained on each sieve. The % of total weight of soil passing through each sieve can be calculated as below.

$$\% \text{ retained on particular sieve} = \frac{\text{Wt. of soil retained on that sieve}}{\text{Total wt. of soil taken}} \times 100$$

Cumulative % retained - Sum of % retained on all sieves of larger sizes & the % retained on that particular

Sieve Sieves	% retained	% Cumulative retained
4.75	10%	
2	20%	30
1	10%	40
600μ	10%	40
425μ		100

% finer than sieve under reference = 100 - Cumulative % retained

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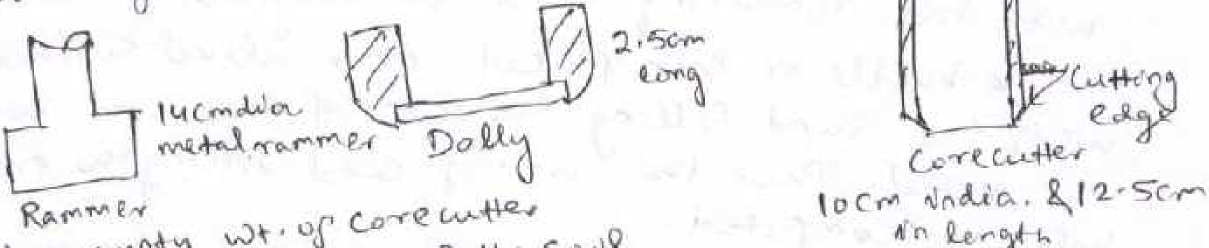
Unit weight of soil :-

Methods for determination
(a) Core cutter method
(b) Water displacement method
(c) Submerged mass density
(d) Sand replacement method

Core cutter method : It is commonly used method for determination of bulk unit weight of soil
- It is used for sticky soil but it is not applicable in case of coarse grained soil.



W_1 = empty wt. of core cutter
W_2 = wt. of core cutter & the soil
$W = W_2 - W_1$ = wt. of soil in the core cutter
Vol. of soil = Internal volume of the core cutter = V

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

Mostly suitable for soft cohesive soils.

For water content determination the soil sample should be collected from the middle of core cutter.

W_1 = wt. of empty container
W_2 = wt. of wet mass of soil + container
W_3 = wt. of dry mass of soil + container

$$w = \frac{W_w}{W_s} \times 100 \qquad W_w = W_3 - W_2$$

$$W_s = W_3 - W_1$$

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

Sand replacement method : The method is suitable for hard or gravelly soils or coarse grained soil.
The sand replacement method consists of making a hole into the ground. The excavated soils is weighed. The volume of the hole is determined by replacement with sand. Knowing the weight of excavated soil & the volume of the hole the in situ unit weight can be determined.

- The site is cleaned & a square tray with a central hole in it is placed on the cleaned surface. A hole of diameter equal to the dia. of the hole in the tray & depth about 10-15cm is made in the ground. The excavated soil is collected in the tray & weighed.

- A sand bottle about 2/3 full of clean dry sand is weighed & placed upside down centrally over the hole.

- The tap is opened & the sand allowed to run to fill the excavated hole & conical end. When no further flow of sand takes place the tap is closed, and the bottle with the remaining sand is weighed.

- The bottle is then placed over a level surface & the weight of sand filling the cone of the sand bottle is noted. Thus the wt. of sand filling the excavated hole is computed.

- The unit weight of sand in bottle is determined by pouring sand in a calibrating can of known dimensions & weighing the sand in calibrating can.

- Having computed the unit weight of sand in the bottle & the weight of sand required to fill the excavated hole the volume of the hole is determined by dividing the wt. of the excavated soil by its volume, the in situ unit wt. of soil is determined.

The water content of the excavated soil is determined & then dry unit wt from this relation

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

- In bouldery soil a large hole about 30cm to 1m & about 30cm to 1m deep is excavated using a circular ring

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