Mechanics of Soils

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Lecture 1

SECTION 1

- Soil Formation
- Particle Size Distribution
- Soil Classification

SECTION 2

- Soil Composition
  - 3-phase material
  - Soil Characterization (particle size, soil plasticity)

Soil Mechanics

- Soil mechanics is the branch of science that deals with the study of physical properties of soil and the behavior of soil masses subjected to various types of forces.
  - Classify soils and rocks
  - Establish engineering properties
  - Ascertain the compressibility
  - Ascertain the shear strength

According to Terzaghi (1948):

"Soil Mechanics is the application of laws of mechanics and hydraulics to engineering problems dealing with sediments and other unconsolidated accumulations of solid particles produced by the mechanical and chemical disintegration of rocks regardless of whether or not they contain an admixture of organic constituent."

Soil Formation

Parent Rock

Residual soil

~ in situ weathering (by physical & chemical agents) of parent rock

Transported soil

~ weathered and transported far away

by wind, water and ice.

Soil Formation

~ formed by one of these three different processes

igneous

formed by cooling of molten magma (lava)

e.g., granite

sedimentary

formed by gradual deposition, and in layers

e.g., limestone, shale

metamorphic

formed by alteration of igneous & sedimentary rocks by pressure/temperature

e.g., marble

Determination of Particle Size Distribution

- Mechanical analysis is used in the determination of the size range of particles present in a soil, expressed as a percentage of the total dry weight.

- There are two methods that generally utilized to determine the particle size distribution of soil:

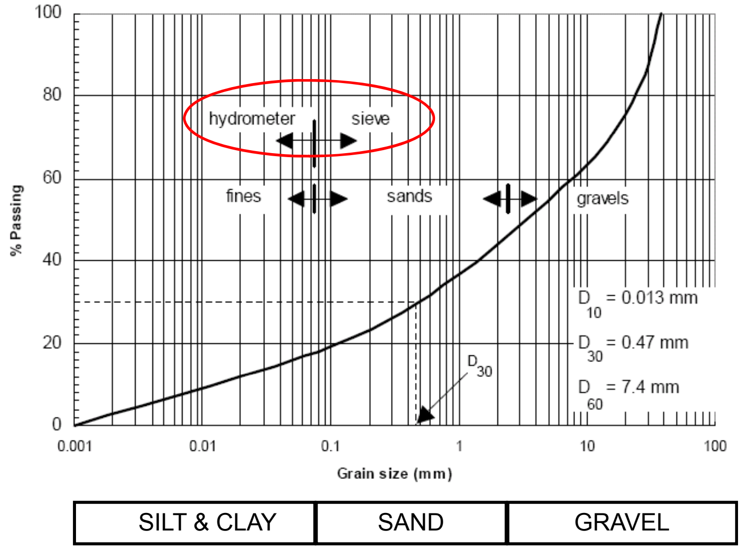
  - Sieve Analysis (for particle sizes > 0.075mm in diameter)
  - Hydrometer Analysis (" " " < 0.075mm " ")

Particle Size Distributions and Soil Particle Characteristics

- Particle size distribution curve is a representation in graphical or tabular form of the various (diameter) grain sizes in a soil, determined through sieving and sedimentation.

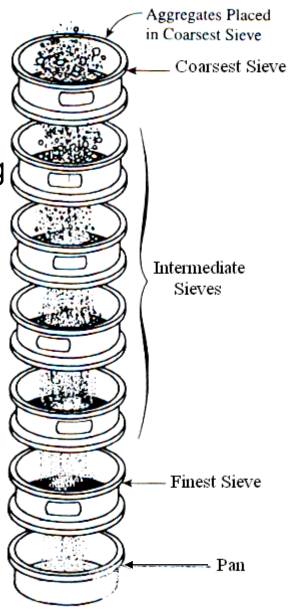
- The particle diameters are plotted in log scale, and the corresponding percent finer in arithmetic scale.

Particle Size Distribution Curve



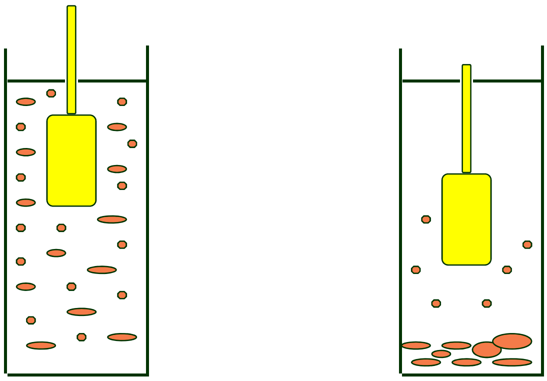
Sieve Analysis

- It is performed by shaking the soil sample through a set of sieves having progressively smaller openings.



Hydrometer Analysis

- It is based on the principle of sedimentation of soil grains in water.

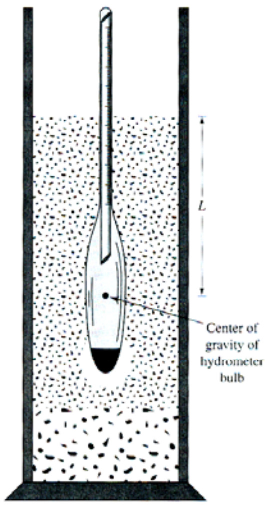


By David Airey, The University of Sydney

Hydrometer Analysis

- Also called Sedimentation Analysis
- Stoke's Law

$$v = \frac{D^2 \gamma_w (G_s - G_L)}{18\eta}$$



Some commonly used measures are:

a) **Effective size :** (D_{10})

It is the diameter in the particle size distribution curve corresponding to 10% finer. (maximum size of the smallest 10% of the soil)

b) **Uniformity Coefficient:** $C_u = D_{60} / D_{10}$

It is the ratio of the maximum diameter of the smallest 60% to the effective size.

- A well graded soil will have $C_u > 4$ for gravels

  $C_u > 6$ for sands

Some commonly used measures are:

c) **Coefficient of Curvature:**

$$C_c = (D_{30})^2 \,/\, (D_{60} * D_{10})$$

D_{30}: Diameter corresponding the 30% finer

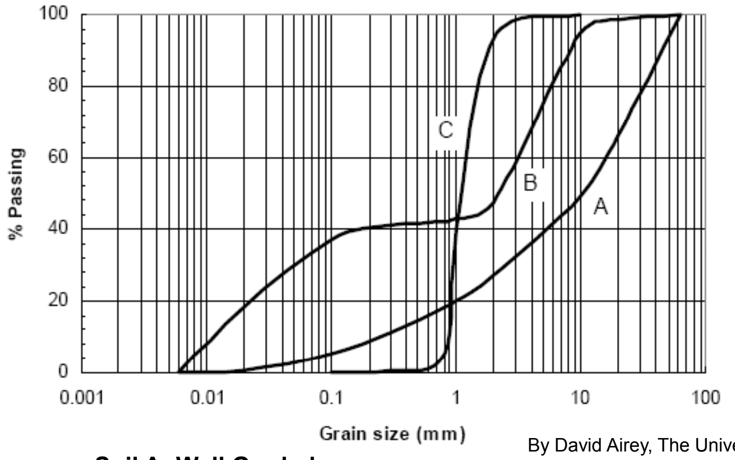
d) **Clay Fraction:** (CF)

It is the percentage by dry mass of particles smaller than 0.002mm (2μm), and is an index property frequently quoted relation to fine grained soils (soils with 50% or more finer than 63μm). It has a strong influence on the engineering properties of fine grained soils.

Definitions

e) **Well-Graded Material** – Contains particles of a wide range of sizes. The smaller particles fill the spaces left between the larger particles; therefore the soil has greater strength than a poorly graded soil, and lower permeability.

f) **Poorly – Graded Material** – Contains a large portion of uniformly sized particles. This particular soil has larger voids in its structure and poor strength along with high permeability.



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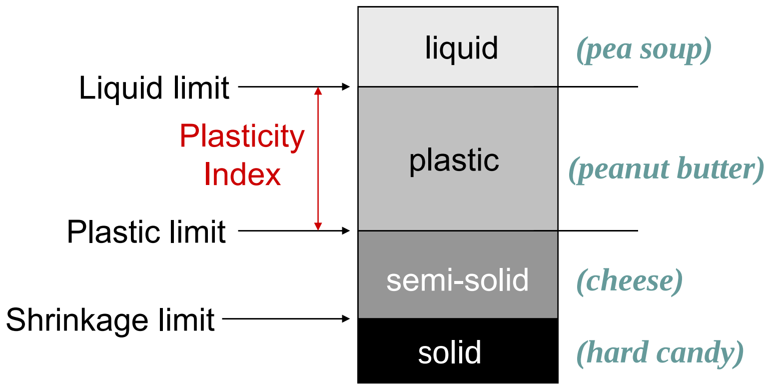
Soil A: Well Graded
Soil B: Poorly Graded
Soil C: Uniform

Soil Plasticity & Consistency Limits

- In the early 1900s a Swedish scientist "**Atterberg**" developed a method to describe the consistency of **fine grained soils** with varying degree of moisture content.
- If a soil is gradually dried from a slurry, it passes from state of viscous liquid to a plastic state; then to a semi-solid, and finally into a solid state. The moisture contents at which the soil passes from one state to the next are known as **consistency limits** (also called "**Atterberg Limits**")
- Consistency limits are utilized to compare soils from different locations and different depths.
- There are 4 basic states

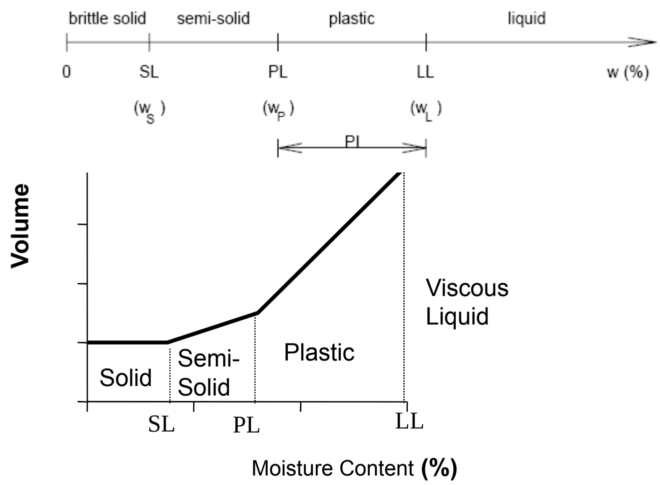
Atterberg Limits

- Consistency of fine-grained soil varies in proportion to the water content



By P. Jayawickrama, Texas Tech University

Consistency Limits



Definitions

a) **Liquid Limit (LL) :** is the minimum moisture content at which the soil will flow under its own weight. The moisture content (in %) required to close a distance of 12.7mm along the bottom of the groove after 25 blows is thell.

b) **Plastic Limit (PL):** is the moisture content (in %) at which the soil when rolled into threads of 3.2mm in diameter, crumbles. PL is the lower limit of the plastic stage of the soil. The test is simple and performed by repeated rollings of ellipsoidal size soil mass by hand on a ground glass plate.

c) **Shrinkage Limit (SL):** is the moisture content (in %) at which the volume change of the soil mass ceases.

Definitions

d) **Plasticity Index (PI):** is a measure of the range of the moisture contents over which a soil is plastic.

$$PI = LL - PL$$

e) **Liquidity Index (LI):** The relative consistency of a cohesive soil in a natural state can be defined by the ratio called LI.

$$LI = (w - PL)/(LL - PL)$$

f) **Activity :** is the ratio of PI to the clay fraction (% by dry weight of particles < 2μm)

$$A = PI / (\text{Clay fraction\%})$$

CLASSIFICATION OF SOILS

- The sizes of particles that make up soil may vary widely depending on the predominant size of particles. Soils are classified as :
  1) Gravel
  2) Sand
  3) Silt
  4) Clay
- The most comprehensive is the Unified Soil Classification System (USCS).

USCS

- This system classifies soils under two broad categories:
  - Coarse Grained Soils -are gravelly and sandy in nature with <50% passing through a #200 sieve (diameter=0.075mm)
    - G :“Gravel”
    - S : “Sand”
  - Fine Grained Soils: have 50% or more passing through the #200 sieve.
    - M: inorganic Silt   O: Organic Silts and Clays
    - C: inorganic Clay   Pt: Peat, muck, highly organic soils

USCS

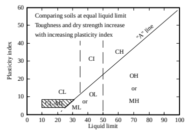
- The standard system used worldwide for most major construction projects is known as the Unified Soil Classification System (USCS).

- This is based on an original system devised by Cassagrande. Soils are identified by symbols determined from

  - Sieve analysis and
  - Atterberg Limit tests.

USCS Table

Unified soil classification (including identification and description)

Field identification procedures (Excluding particles larger than 75mm and basing fractions on estimated weights)				Group symbols 1	Typical names	Information required for describing soils	Laboratory classification criteria	
Coarse grained soils More than half of material is larger than .075mm sieve size	Gravels More than half of coarse fraction is larger than 2.36mm	Clean gravels (little or no fines)	Wide range of grain size and substantial amounts of all intermediate particle sizes	GW	Well graded gravels, gravel-sand mixtures, little or no fines	Give typical names: indicate approximate percentages of sand and gravel: maximum size: angularity, surface condition, and hardness of the coarse grains: local or geological name and other pertinent descriptive information and symbol in parentheses. For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions and drainage characteristics. *Example:* Silty sand, gravelly; about 20% hard angular gravel particles 12.5mm maximum size; rounded and subangular sand grains coarse to fine, about 15% non-plastic lines with low dry strength; well compacted and moist in places; alluvial sand; (SM)	$C_U = \frac{D_{60}}{D_{10}}$ Greater than 4; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			Predominantly one size or a range of sizes with some intermediate sizes missing	GP	Poorly graded gravels, gravel-sand mixtures, little or no fines		Not meeting all gradation requirements for GW	
		Gravels with fines (appreciable amount of fines)	Non-plastic fines (for identification procedures see ML below)	GM	Silty gravels, poorly graded gravel-sand-silt mixtures		Atterberg limits below "A" line or PI less than 4	Above "A" line with PI between 4 and 7 are borderline cases requiring use of dual symbols
			Plastic fines (for identification procedures see CL below)	GC	Clayey gravels, poorly graded gravel-sand-clay mixtures		Atterberg limits above "A" line with PI greater than 7	
	Sands More than half of coarse fraction is smaller than 2.36mm	Clean sands (little or no fines)	Wide range in grain sizes and substantial amounts of all intermediate particle sizes	SW	Well graded sands, gravelly sands, little or no fines		$C_U = \frac{D_{60}}{D_{10}}$ Greater than 6; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			Predominantely one size or a range of sizes with some intermediate sizes missing	SP	Poorly graded sands, gravelly sands, little or no fines		Not meeting all gradation requirements for SW	
		Sands with fines (appreciable amount of fines)	Non-plastic fines (for identification procedures, see ML below)	SM	Silty sands, poorly graded sand-silt mixtures		Atterberg limits below "A" line or PI less than 4	Above "A" line with PI between 4 and 7 are borderline cases requiring use of dual symbols
			Plastic fines (for identification procedures, see CL below)	SC	Clayey sands, poorly graded sand-clay mixtures		Atterberg limits above "A" line with PI greater than 7	
Fine grained soils More than half of material is smaller than .075mm sieve size	Identification procedure on fraction smaller than .425mm sieve size		*Dry strength crushing characteristics / Dilatency (reaction to shaking) / Toughness (consistency near plastic limit)*					
	Silts and clays liquid limit less than 50		None to slight / Quick to slow / None	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	Give typical name; indicate degree and character of plasticity, amount and maximum size of coarse grains: colour in wet condition, odour if any, local or geological name, and other pertinent descriptive information, and symbol in parentheses. For undisturbed soils add information on structure, stratification, consistency and undisturbed and remoulded states, moisture and drainage conditions. *Example* Clayey silt, brown: slightly plastic: small percentage of fine sand: numerous vertical root holes: firm and dry in places; loess; (ML)	 Plasticity chart for laboratory classification of fine grained soils	
			Medium to high / None to very slow / Medium	CL,CI	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays			
			Slight to medium / Slow / Slight	OL	Organic silts and organic silt-clays of low plasticity			
	Silts and clays liquid limit greater than 50		Slight to medium / Slow to none / Slight to medium	MH	inorganic silts, micaceous or dictomaceous fine sandy or silty soils, elastic silts			
			High to very high / None / High	CH	Inorganic clays of high plasticity, fat clays			
			Medium to high / None to very high / Slight to medium	OH	Organic clays of medium to high plasticity			
Highly organic soils			Readily identified by colour, odour spongy feel and frequently by fibrous texture	Pt	Peat and other highly organic soils			

The .075mm sieve size is about the smallest particle visible to the naked eye

Use grain size curve in identifying the fractions as given under field identification

Determine percentages of gravel and sand from grain size curve

Depending on percentages of fines (fraction smaller than .075mm sieve size) coarse grained soils are classified as follows

Less than 5% GW, GP, SW, SP

More than 12% GM, GC, SM, SC

5% to 12% Bordeline case requiring use of dual symbols

Classification Procedure

- <u>Coarse Grained Materials</u>
  - If more than half of the material is coarser than the 75 μm sieve, the soil is classified as coarse. The following steps are then followed to determine the appropriate 2 letter symbol
  - Determine the1st letter of the symbol
    - If more than half of the coarse fraction is sand then use prefix **S**
    - If more than half of the coarse fraction is gravel then use prefix **G**
  - Determine the 2nd letter of symbol
    - This depends on the uniformity coefficient Cu and the coefficient of curvature Cc obtained from the grading curve, on the percentage of fines, and the type of fines.

Classification Procedure

- First determine the percentage of fines, that is the % of material passing the 75 μm sieve.
- Then if % fines is
  - < 5% use W or P as suffix
  - > 12% use M or C as suffix
  - between 5% and 12% use dual symbols. Use the prefix from above with first one of W or P and then with one of M or C.
  - If W or P are required for the suffix then Cu and Cc must be evaluated
- If prefix is **G** then suffix is **W** if Cu > 4 and Cc is between 1 & 3
  otherwise use **P**
- If prefix is **S** then suffix is **W** if Cu > 6 and Cc is between 1 & 3
  otherwise use **P**

Classification Procedure

- If M or C are required they have to be determined from the procedure used for fine grained materials discussed below. Note that M stands for Silt and C for Clay. This is determined from whether the soil lies above or below the A-line in the plasticity chart.
- For a coarse grained soil which is predominantly sand the following symbols are possible
- SW, SP, SM, SC
- SW-SM, SW-SC, SP-SM, SP-SC

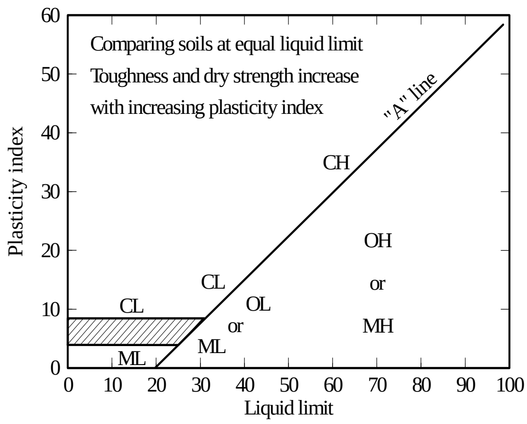
Classification Procedure

- These are classified solely according to the results from the Atterberg Limit Tests. Values of the Plasticity Index and Liquid Limit are used to determine a point in the plasticity chart. The classification symbol is determined from the region of the chart in which the point lies.

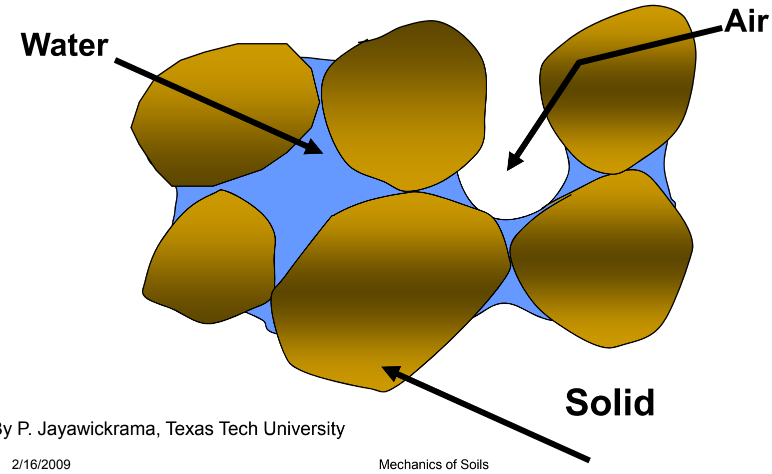
Examples

- CH High plasticity clay
- CL Low plasticity clay
- MH High plasticity silt
- ML Low plasticity silt
- OH High plasticity organic soil (Rare)
- Pt Peat

Casagrande Plasticity Chart

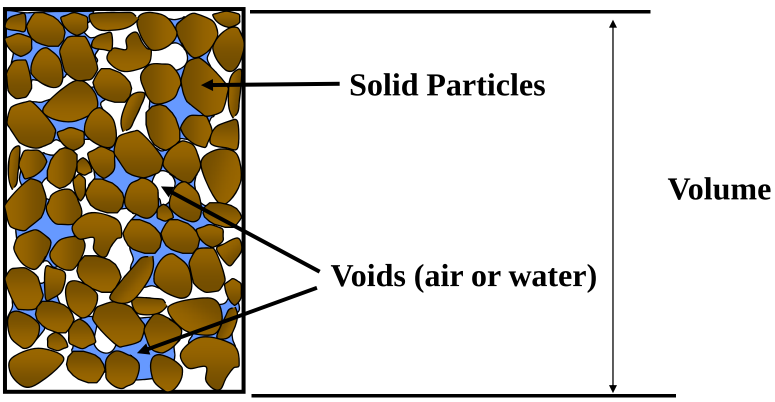


3-Phase Material

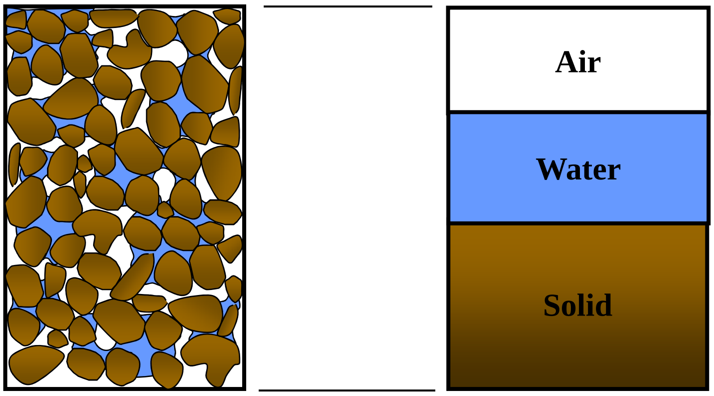


By P. Jayawickrama, Texas Tech University

The Mineral Skeleton



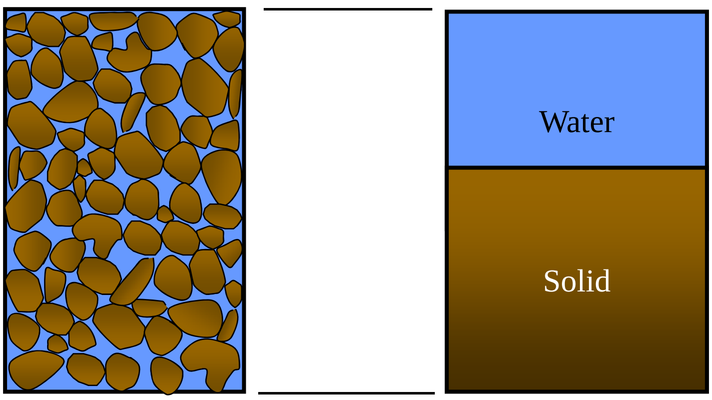
Three Phase Diagram



Mineral Skeleton

Idealization:
Three Phase Diagram

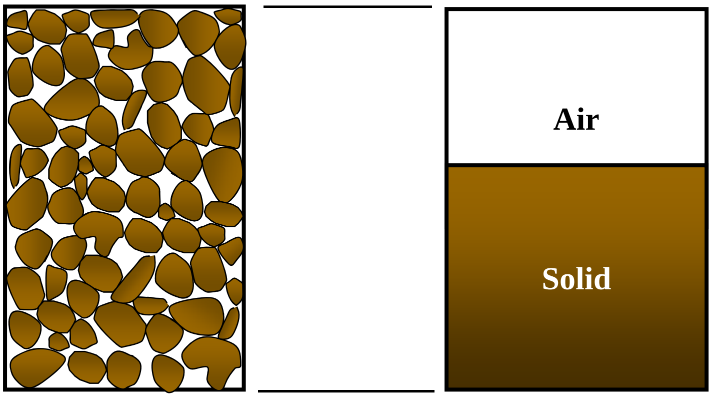
Fully Saturated Soils



Mineral Skeleton

Fully Saturated

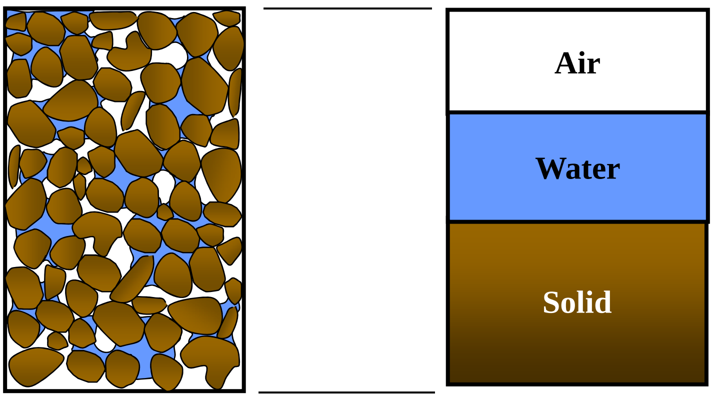
Dry Soils



Mineral Skeleton

Dry Soil

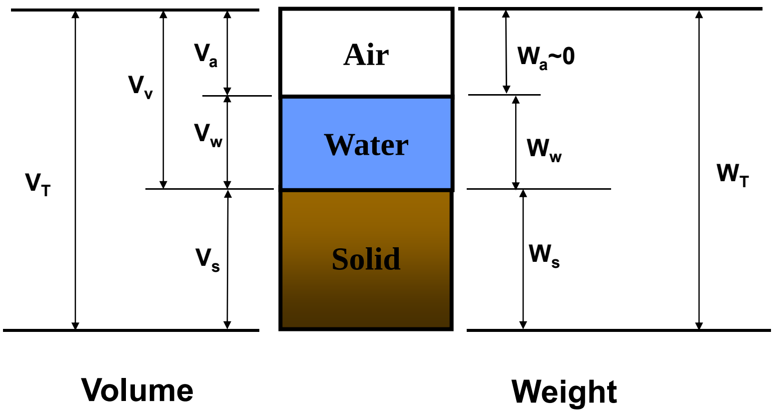
Partly Saturated Soils



Mineral Skeleton

Partly Saturated Soils

Phase Diagram



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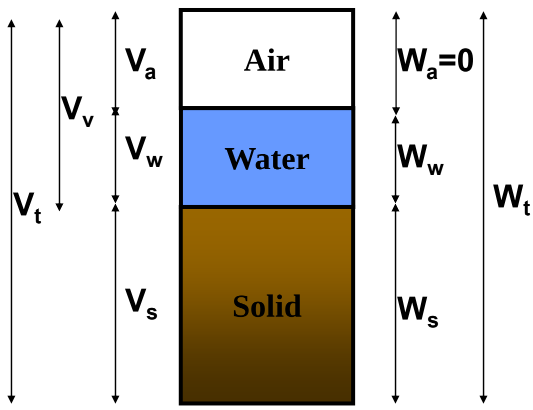
Objectives of a Phase Diagram

To compute the weights (or masses) and volumes of the three different phases.

Notation
M = mass or weight
V = volume
s = soil grains
w = water
a = air
v = voids
t = total



Phase Diagram

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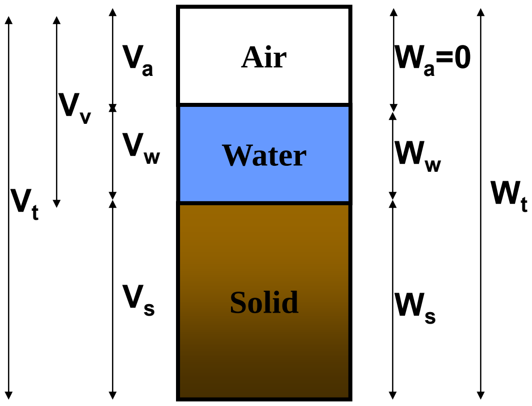
Volume Relationships

Void ratio (e): is a measure of the void volume.

$$e = \frac{V_V}{V_S}$$



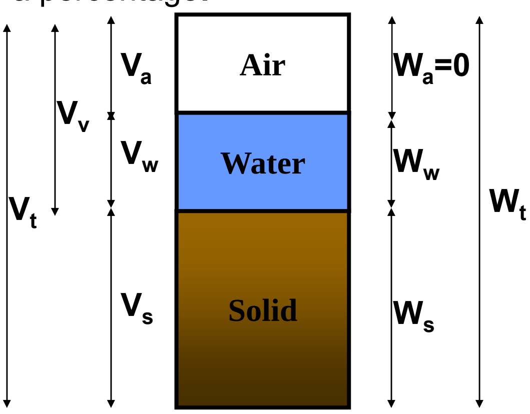
Phase Diagram

Volume Relationships

Porosity (n): is also a measure of the void volume, expressed as a percentage.

$$n = \frac{V_V}{V_T} \text{ X } 100\%$$

Theoretical range: 0 – 100%



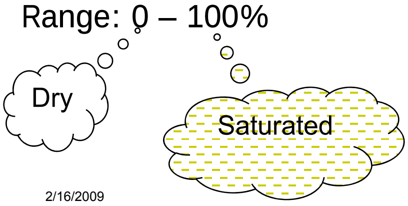
Phase Diagram

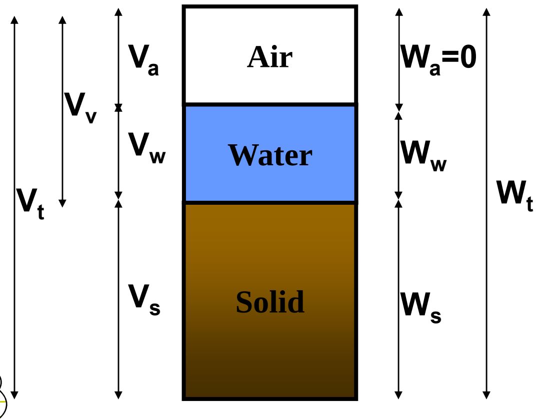
Volume Relationships

Degree of saturation (S): is the percentage of the void volume filled by water.

$$S = \frac{V_W}{V_V} \text{ X } 100\%$$

Range: 0 – 100%





Phase Diagram

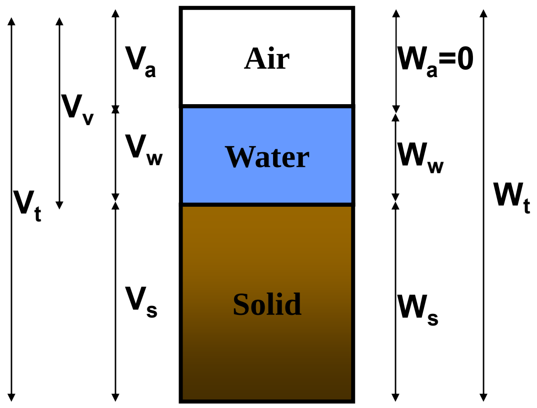
Weight Relationships

Water content (w): is a measure of the water present in the soil.

$$w = \frac{W_W}{W_S} \text{ X } 100\%$$

Expressed as percentage.

Range = 0 – 100%.



Phase Diagram

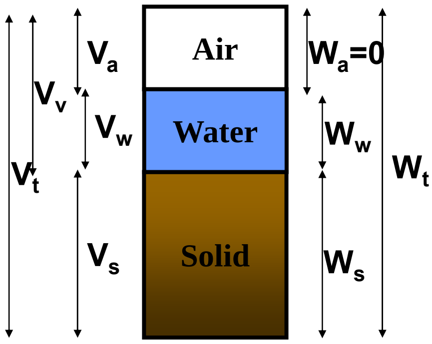
Unit Weight Relationships

Natural Unit Weight (γ): is the density of the soil in the current state.

$$\gamma = \frac{W_T}{V_T}$$

Dry Unit Weight (γ_d): is the unit weight of the soil in dry state.

$$\gamma_d = \frac{W_S}{V_T}$$



Phase Diagram

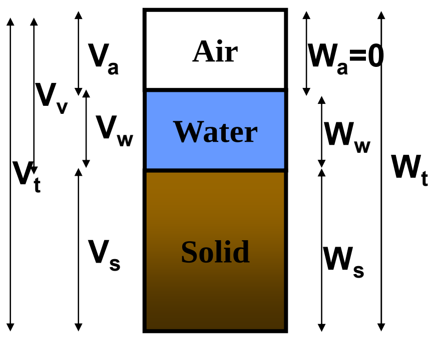
Unit Weight Relationships

Saturated Unit Weight (γ_{sat}): is the unit weight of the soil when the voids are filled with water.

$$\gamma_{sat} = \frac{W_S + V_V * \gamma_w}{V_T}$$

Submerged Unit Weight (γ_{sub}): is the effective unit weight of the soil when it is submerged.

$$\gamma_{sub} = \gamma_{sat} - \gamma_w$$



Phase Diagram

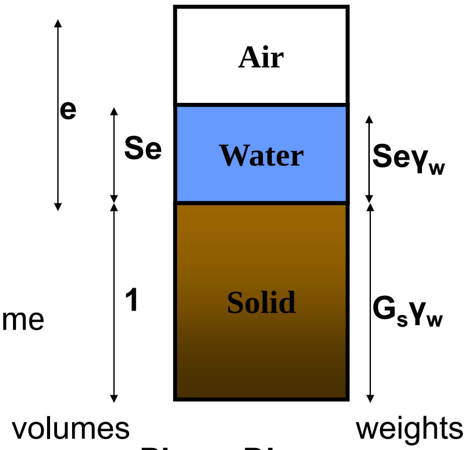
Phase Relations

Consider a fraction of the soil where $V_s = 1$.

The other volumes can be obtained from the previous definitions.

The weights can be obtained from:

Weights = Unit Weights x Volume



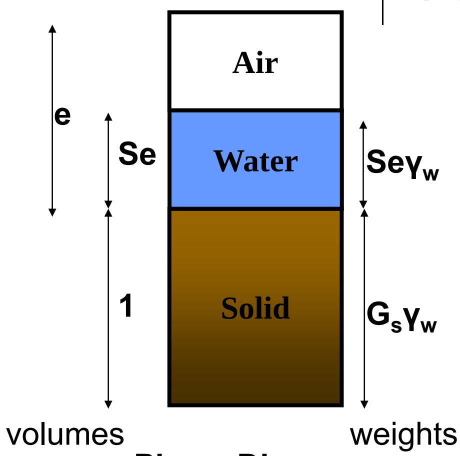
Phase Diagram

Phase Relations

From the previous definitions,

$$w = \frac{W_W}{W_S} = \frac{Se}{G_S}$$

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



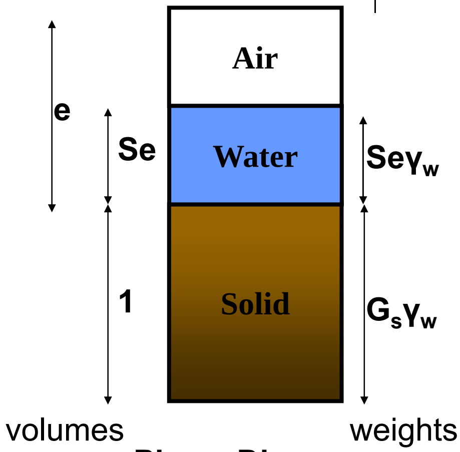
Phase Diagram

Phase Relations

$$\gamma = \frac{W_T}{V_T} = \frac{G_S + Se}{1+e}\gamma_W$$

$$\gamma_{sat} = \frac{W_T}{V_T} = \frac{G_S + e}{1+e}\gamma_W$$

$$\gamma_d = \frac{W_S}{V_T} = \frac{G_S}{1+e}\gamma_W$$



Phase Diagram

Definitions

Bulk (natural), saturated, dry and submerged densities (ρ) are defined in a similar manner.

Here, you can also use mass (kg) instead of weight (kN).

$$\gamma \,/\, g = \rho = M/V$$

γ: N/m³ — g: m/s² — ρ: kg/m³

Specific Gravity

$$G_S = \frac{\text{Weight of a Substance}}{\text{Weight of an Equal Volume of Water}}$$

$$G_S = \frac{\text{Unit Weight of a Substance}}{\text{Unit Weight of Water}}$$

- Unit weight of Water, γ_w
  - γ_w = 1.0 g/cm^3 (strictly accurate at 4° C)
  - γ_w = 9.81 kN/m^3

In Terms of Density

i. Density of water : ρ_w = 1000kg/m^3

ii. Dry density of soil : $\rho_d = \frac{M_S}{V_T} = \frac{G_S}{1+e}\rho_W$

iii. Bulk density of unsaturated or saturated soil: $\rho = \frac{M_T}{V_T} = \frac{G_S + Se}{1+e}\rho_W$

iv. Air content (A) : $A = \frac{V_a}{V_T} = \frac{e - G_S w}{1+e}$

Relationship between parameters

- These definitions can be used to determine any desired relationships between above quantities, and hence to determine void ratio, degree of saturation, etc. That can not be measured directly by laboratory tests. Some relationships are as follows:

Relationship between parameters

- For unsaturated soils:

$$w = \frac{W_W}{W_S} = \frac{Se}{G_S} \Rightarrow e = \frac{G_S w}{S} \quad [1]$$

- For saturated soils: S = 1 then; $e = G_S w$
- Bulk density; $\rho = \frac{M_T}{V_T} = \frac{G_S + Se}{1+e}\rho_W \Rightarrow \rho = \frac{(G_S w + G_S)}{1+e}\rho_w = \frac{G_S(w+1)\rho_w}{1+e}$
- Dry density; $\rho_d = \frac{M_S}{V_T} = \frac{G_S}{1+e}\rho_W \Rightarrow \rho_d(1+w) = \rho$
- Degree of Saturation; $S = \frac{G_S w \rho}{(1+w)G_S\rho_w - \rho}$

By N. Sivakugan

- Try not to *memorize* the equations. ***Understand*** the definitions, and develop the relations from the phase diagram with $V_S = 1$;
- Assume G_S (2.6-2.8) when not given;
- Do not mix densities and unit weights;
- Soil grains are incompressible. Their mass and volume remain the same at any void ratio.