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Soil Mechanics

Bassam Z. Mahasneh (PhD.)
Professor (full)
Civil and Environmental Eng. Dept.
Mutah University

Soils - What are they?

- Soil Mechanics is concerned with Particulate materials
- - Sedimentary origins (usually)
- - Residual
- Wide range of particle sizes
- - larger particles: quartz, feldspar
- - very small particles: clay minerals kaolin, illite and montmorillonite, minerals that have low strengths and form plate like particles
- Voids between particles. One of the most important aspects of particulate materials is that there are gaps or voids between the particles. The amount of voids is also influenced by the size, shape and mineralogy of the particles.

Soil Formations and Deposits

What is a soil? Soil is defined as the uncemented aggregate of mineral grains and decayed organic matter with liquid and/or gas in the pores between the grains

(A) gas (mostly air); (B) solid particles (minerals); (C) liquid (water, contaminant liquid, etc.);

Where did soil come from?

Soils are formed by weathering of rocks. More specifically, the mineral grains that form the solid phase of a soil aggregate are the product of rock weathering. So that, we need discuss (a) rocks and rock type; (b) weathering of rocks;

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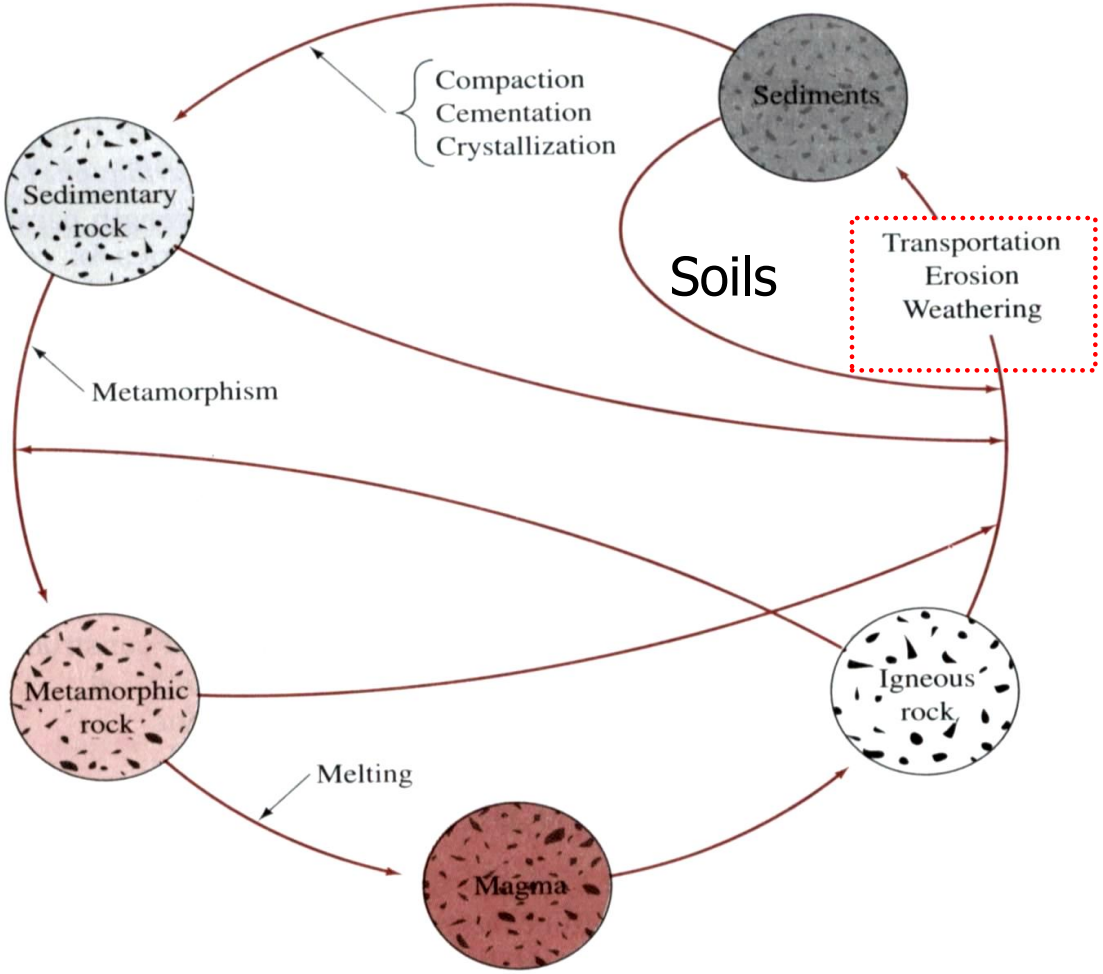
Rock Cycles



The final products due to weathering

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Weathering

- 1 Physical processes of weathering
  - Unloading
    - e.g. uplift, erosion, or change in fluid pressure.
  - Thermal expansion and contraction
  - Alternate wetting and drying
  - Crystal growth, including frost action
  - Organic activity
    - e.g. the growth of plant roots.
- 2 Chemical Process of weathering
  - Hydrolysis
    - is the reaction with water
    - will not continue in the static water.
    - involves solubility of silica and alumina
  - Chelation
    - Involves the complexing and removal of metal ions .
  - Cation exchange
    - is important to the formation of clay minerals
  - Oxidation and reduction.
  - Carbonation
    - is the combination of carbonate ions such as the reaction with CO_2
- 3 Factors affect weathering
  - Many factors can affect the weathering process such as climate, topography, features of parent rocks, biological reactions, and others.
  - Climate determines the amount of water and the temperature.

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Transported Soils

•(1) **Glacial soils**: formed by transportation and deposition of glaciers.

•(2) **Alluvial soils**: transported by running water and deposited along streams.

•(3) **Lacustrine soils**: formed by deposition in quiet lakes (e.g. soils in Taipei basin).

•(4) **Marine soils**: formed by deposition in the seas (Hong Kong).

•(5) **Aeolian soils**: transported and deposited by the wind (e.g. soils in the loess plateau, China).

•(6) **Colluvial soils**: formed by movement of soil from its original place by gravity, such as during landslide (*Hong Kong*). (from Das, 1998)

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Origin of Clay Minerals

- "The contact of rocks and water produces clays, either at or near the surface of the earth".
- **Rock +Water → Clay**
- For example,
- The CO_2 gas can dissolve in water and form carbonic acid, which will become hydrogen ions H^+ and bicarbonate ions, and make water slightly acidic.
- $CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$
- The acidic water will react with the rock surfaces and tend to dissolve the K ion and silica from the feldspar. Finally, the feldspar is transformed into kaolinite.
- Feldspar + hydrogen ions + water → clay (kaolinite) + cations, dissolved silica
- $2KAlSi_3O_8 + 2H^+ + H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 4SiO_2$
- Note that the hydrogen ion displaces the cations.

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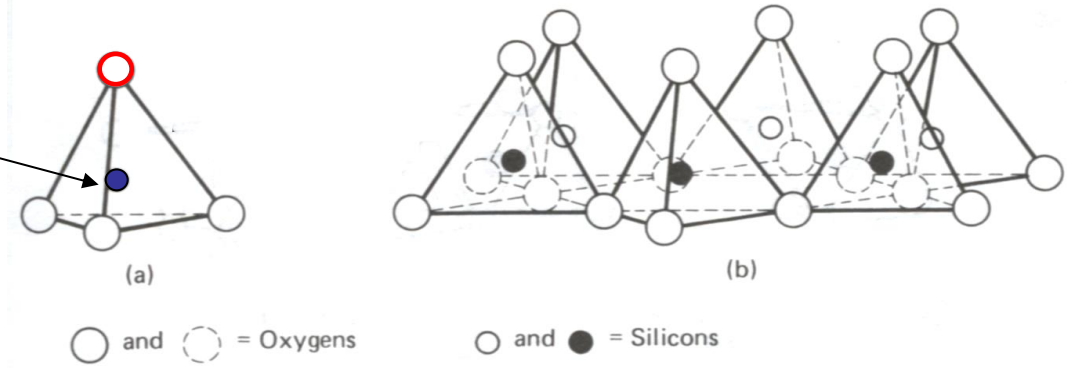
Basic Unit-Silica Tetrahedra

1 Si

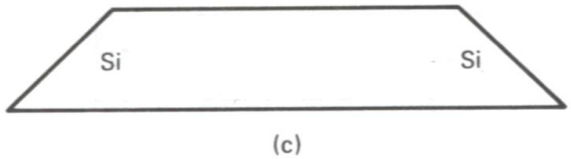
4 O



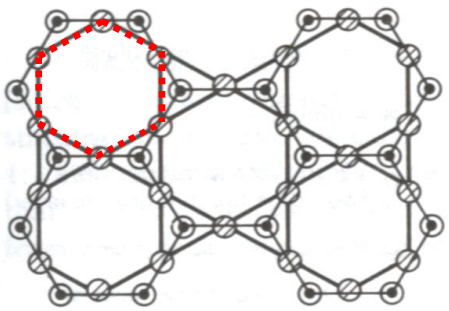
$(Si_2O_{10})^{-4}$

Replace four Oxygen with hydroxyls or combine with positive union

- Quartz $SiO_2 \times 4 = Si_4O_8$
- K Feldspar $KAlSi_3O_8$



Hexagonal hole



Oxygens in plane above silicons

Silicons

Oxygens linked to form network

Outline of bases of silica tetrahedra

Outline of hexagonal silica network (two dimensional); also indicates bonds from silicons to oxygens in lower plane (fourth bond from each silicon is perpendicular to plane of paper)

Tetrahedron

Plural: Tetrahedra

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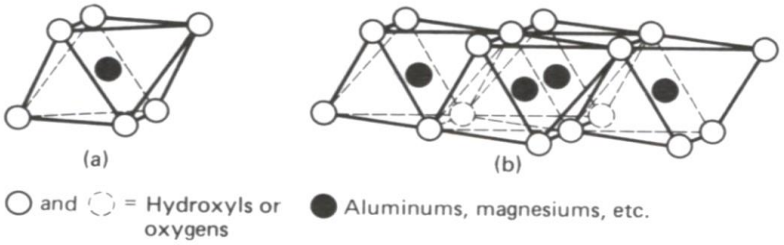
Basic Unit-Octahedral Sheet

1 Cation

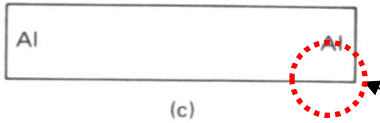
6 O or OH



Gibbsite sheet: Al^{3+}

$Al_2(OH)_6$, 2/3 cationic spaces are filled

One OH is surrounded by 2 Al:
Dioctahedral sheet

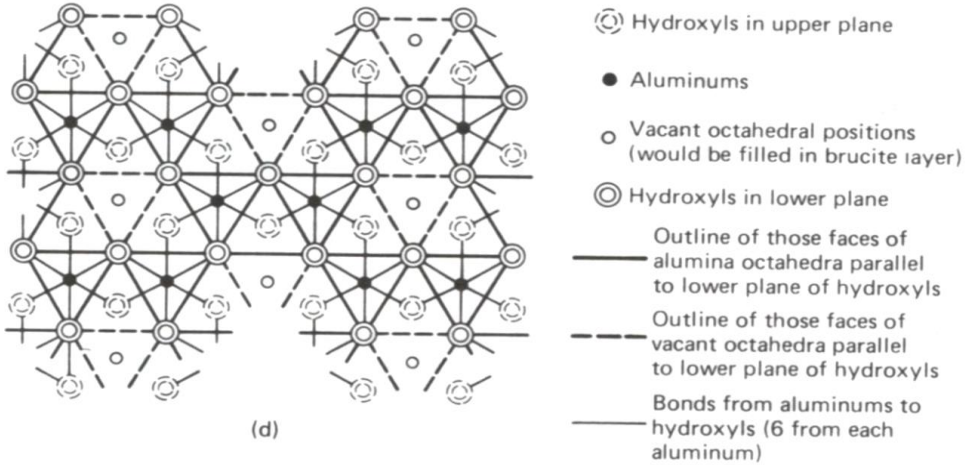


Different cations

Brucite sheet: Mg^{2+}

$Mg_3(OH)_6$, all cationic spaces are filled

One OH is surrounded by 3 Mg:
Trioctahedral sheet



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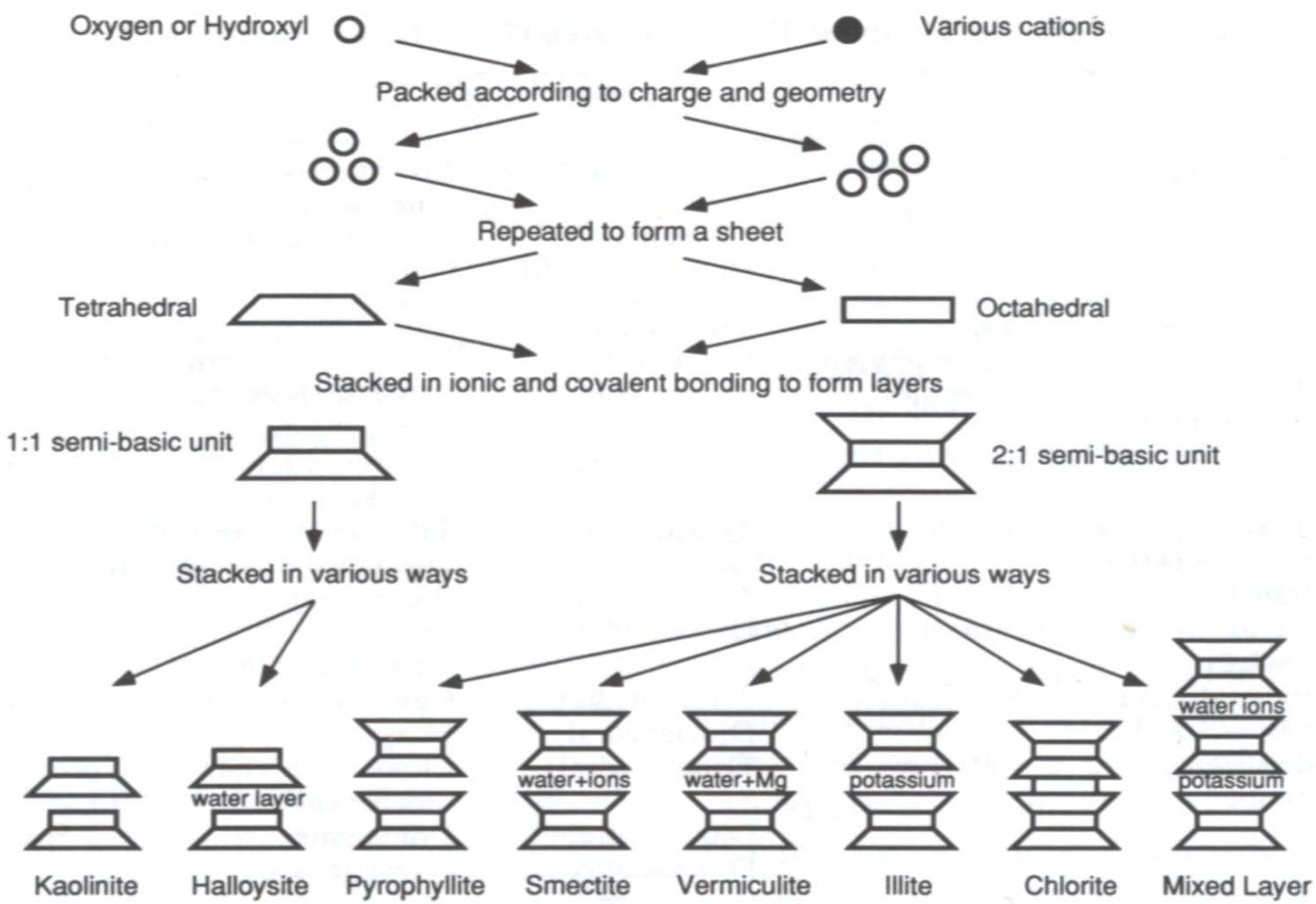
Synthesis



Noncrystalline clay - allophane

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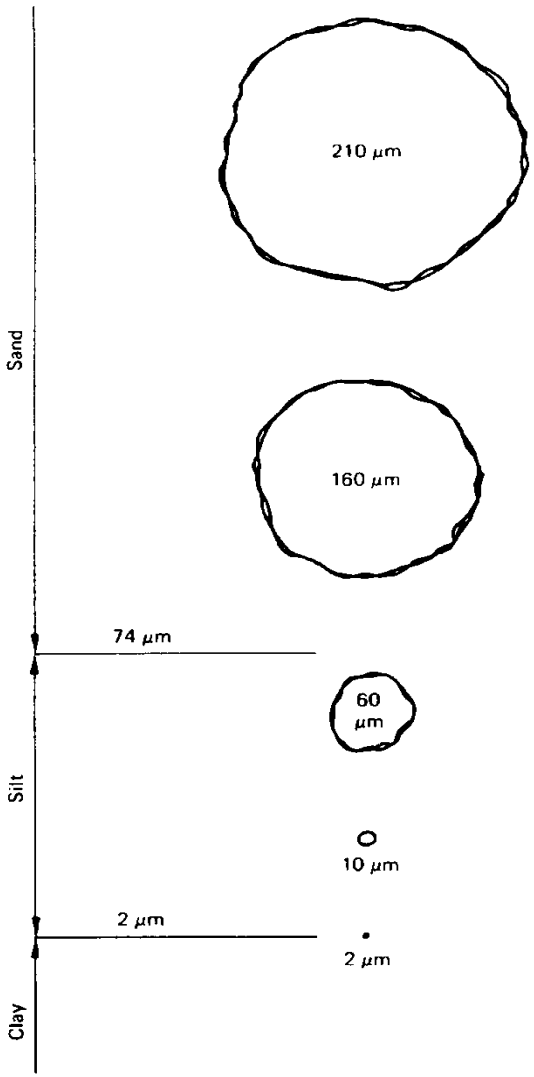
Clay Formation

- Clay particles < 2 μm
- Compared to Sands and Silts, clay size particles have undergone a lot more "chemical weathering"!



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Clay vs. Sand/Silt

- Clay particles are generally more platy in shape (sand more equi-dimensional)
- Clay particles carry surface charge
- Amount of surface charge depends on type of clay minerals
- Surface charges that exist on clay particles have major influence on their behavior (for e.g. plasticity)

Clay Minerals

- Kaolinite family
  - Kaolinite (ceramic industry, paper, paint, pharmaceutical)
- Smectite family
  - Montmorillonite (weathered volcanic ash, Wyoming Bentonite, highly expansive, used in drilling mud)
- Illite family

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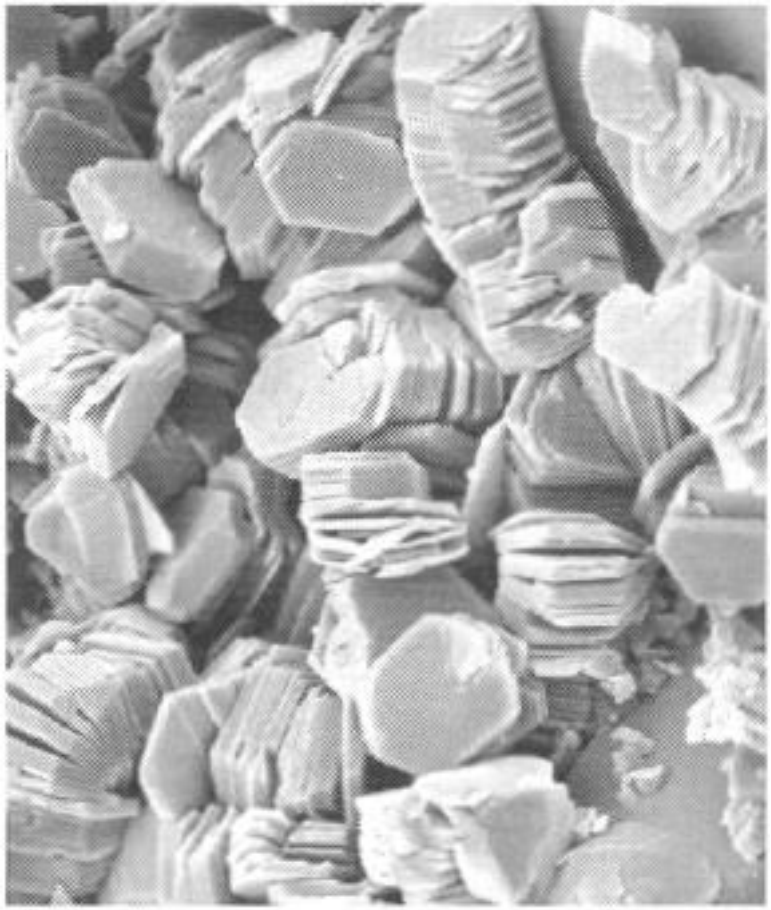
Clay Morphology

- Scanning Electron Microscope (SEM)
- Allows us to study morphology of clay minerals
- Used in mineral identification



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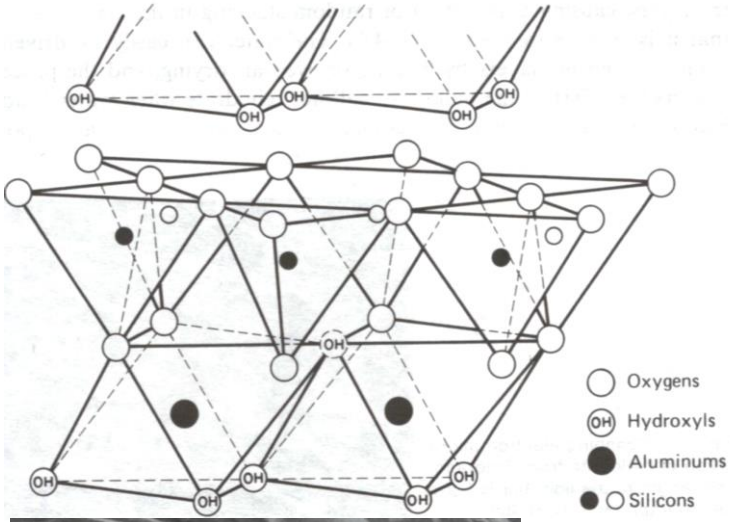
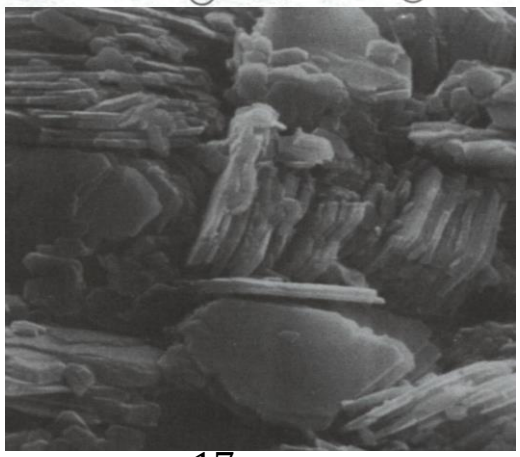
Minerals-Kaolinite

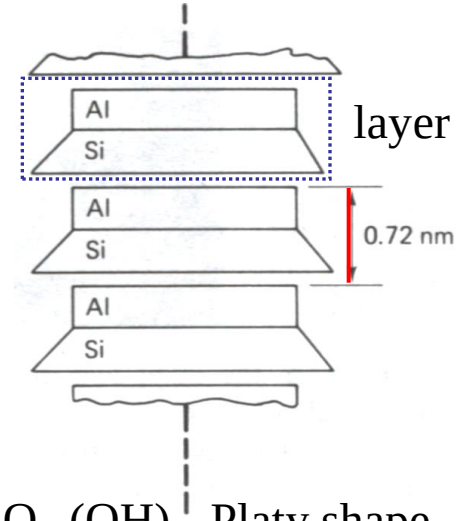




17 μm

Trovey, 1971 (from Mitchell, 1993)

Basal spacing is 7.2 Å



- $Si_4Al_4O_{10}(OH)_8$. Platy shape
- The bonding between layers are van der Waals forces and hydrogen bonds (strong bonding).
- There is no interlayer swelling
- Width: 0.1~ 4μm, Thickness: 0.05~2 μm

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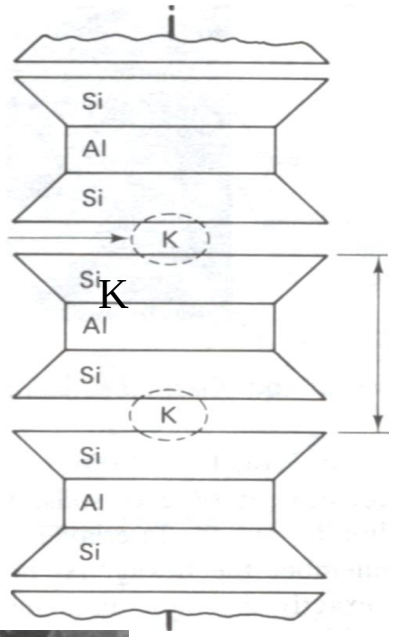
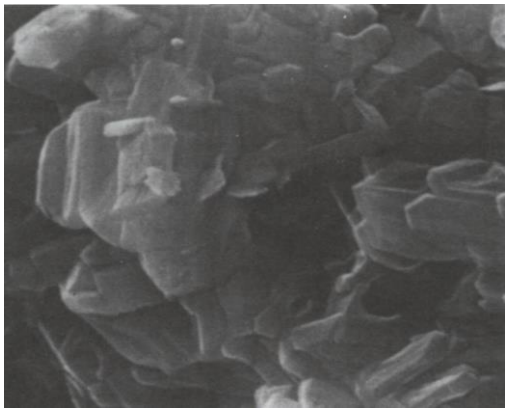
Minerals-Illite (mica-like minerals)

potassium





7.5 μm

Trovey, 1971 (from Mitchell, 1993)

- $Si_8(Al,Mg, Fe)_{4\sim6}O_{20}(OH)_4\cdot(K,H_2O)_2$. Flaky shape.
- The basic structure is very similar to the mica, so it is sometimes referred to as hydrous mica. Illite is the chief constituent in many shales.
- Some of the Si^{4+} in the tetrahedral sheet are replaced by the Al^{3+}, and some of the Al^{3+} in the octahedral sheet are substituted by the Mg^{2+} or Fe^{3+}. Those are the origins of charge deficiencies.
- The charge deficiency is balanced by the potassium ion between layers. Note that the potassium atom can exactly fit into the hexagonal hole in the tetrahedral sheet and form a strong interlayer bonding.
- The basal spacing is fixed at 10 Å in the presence of polar liquids (no interlayer swelling).
- Width: 0.1~ several μm, Thickness: ~ 30 Å

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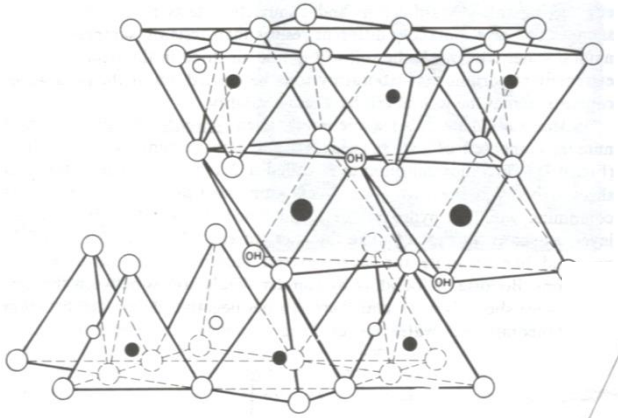
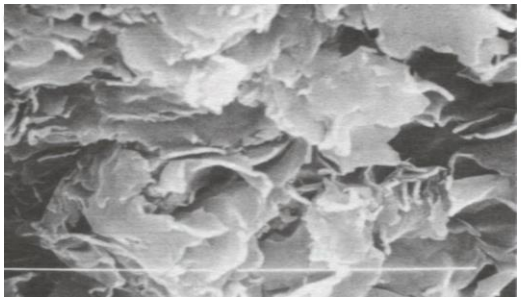
Minerals-Montmorillonite

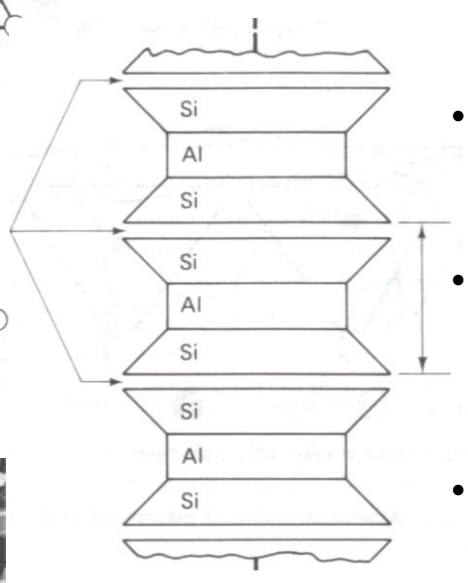


$n \cdot H_2O$+cations



5 μm

(Holtz and Kovacs, 1981)



- $Si_8Al_4O_{20}(OH)_4 \cdot nH_2O$ (Theoretical unsubstituted). Film-like shape.
- There is extensive isomorphous substitution for silicon and aluminum by other cations, which results in charge deficiencies of clay particles.
- $n \cdot H_2O$ and cations exist between unit layers, and the basal spacing is from 9.6 Å to ∞ (after swelling).
- The interlayer bonding is by van der Waals forces and by cations which balance charge deficiencies (weak bonding).
- There exists interlayer swelling, which is very important to engineering practice (**expansive clay**).
- Width: 1 or 2 μm, Thickness: 10 Å~1/100 width

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Exchangeable ions and Double layer

The surface of clay mineral particles carries residual negative charges due to Isomorphous substitution and other reasons.

To neutralize these negative charges, the particle attracts positive (cations +) from dissolved salts in the pore water forming what is known as the double layer.

The cations can be replaced or exchanged by another type of cations (e.g. Na+, Ca++).

Therefore these ions re called "Exchangeable ions".

The cations and the attracted water are strongly held to the particles by hydrogen bonding and attraction between (+) and (-) charges, therefore this water is called adsorbed water.

It is not free water, it can not be separated by heating.

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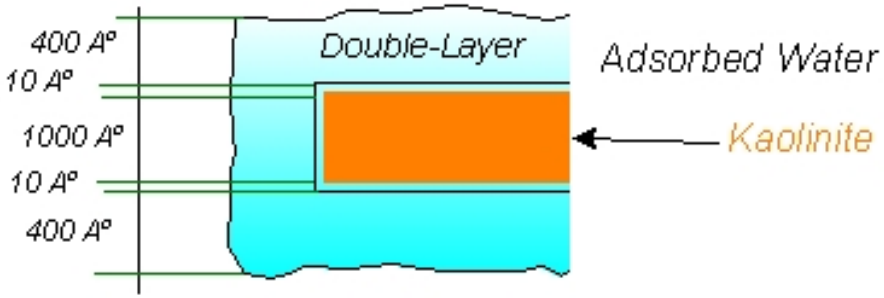

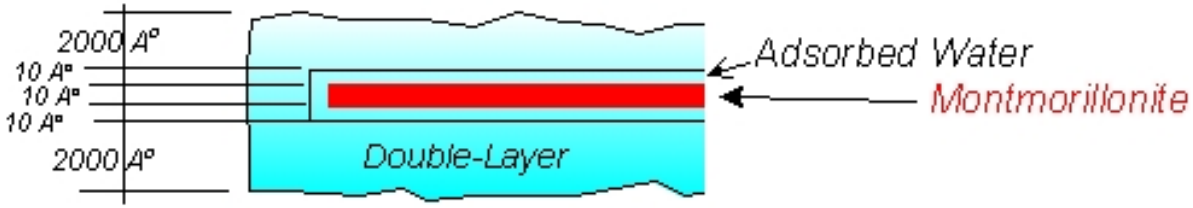

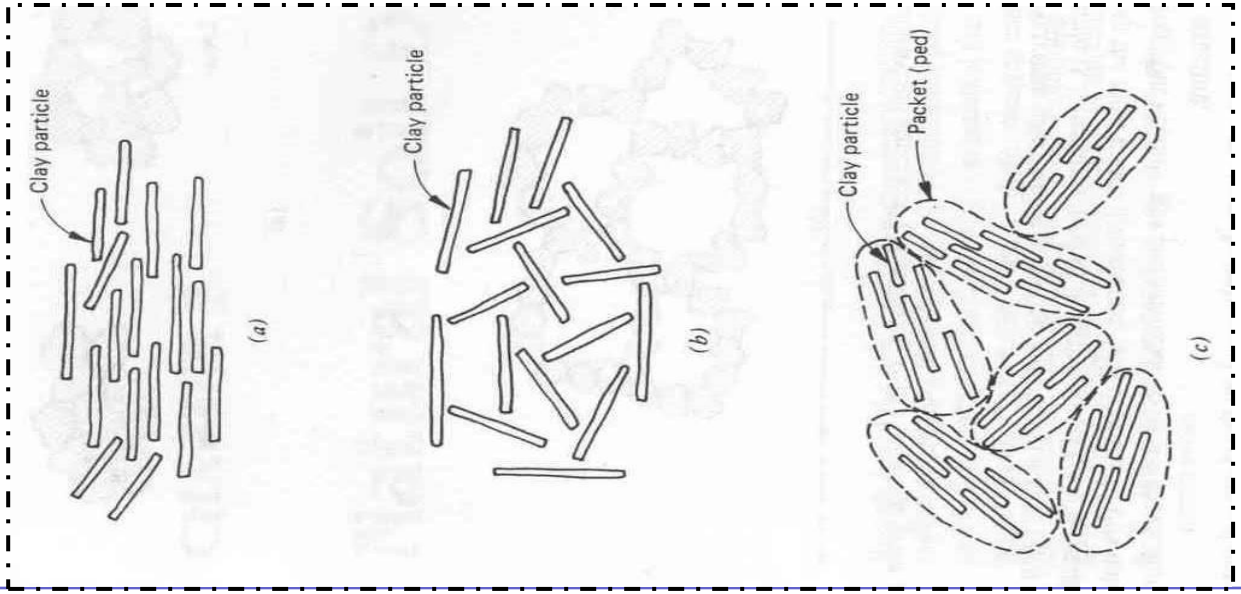

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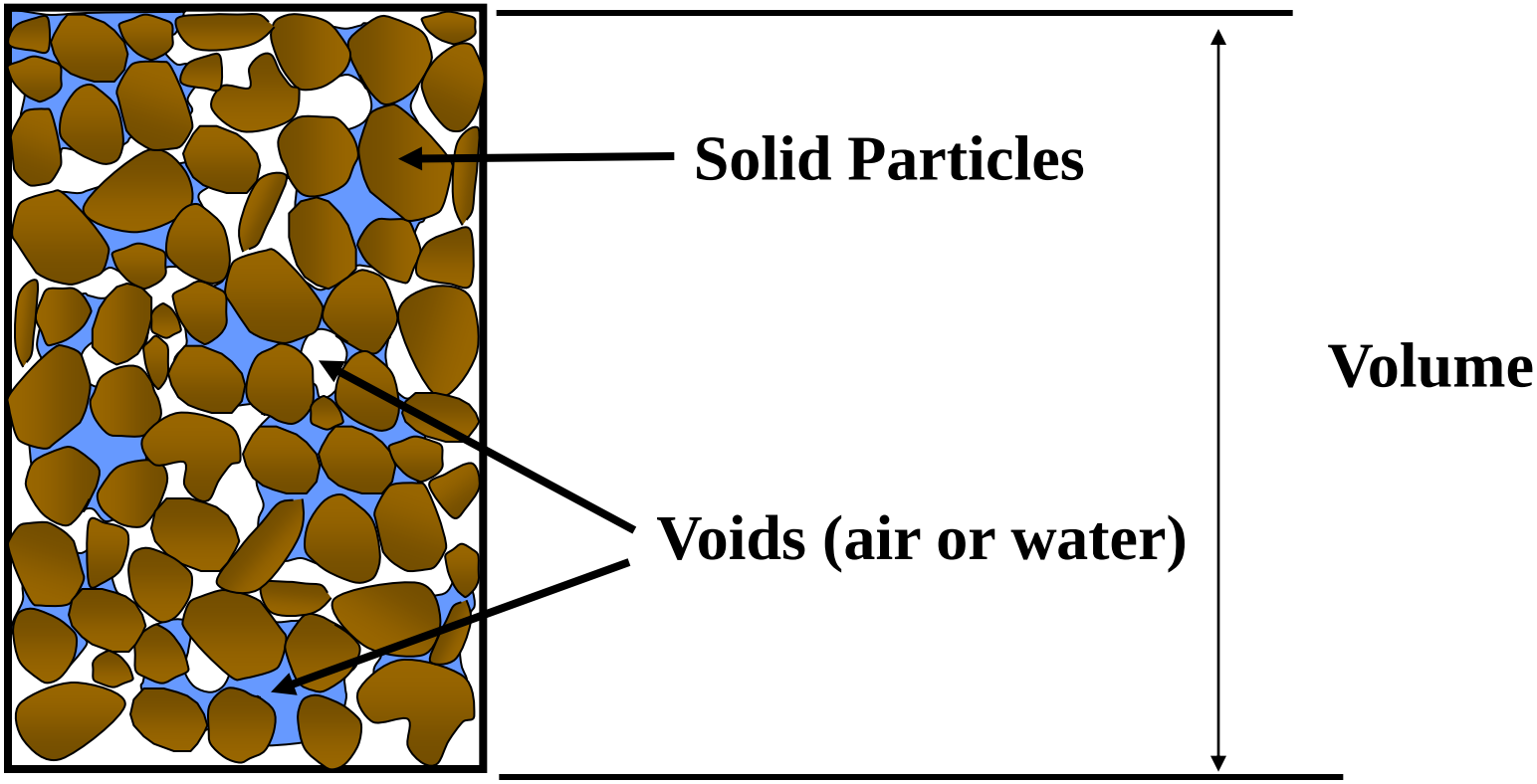
The Mineral Skeleton



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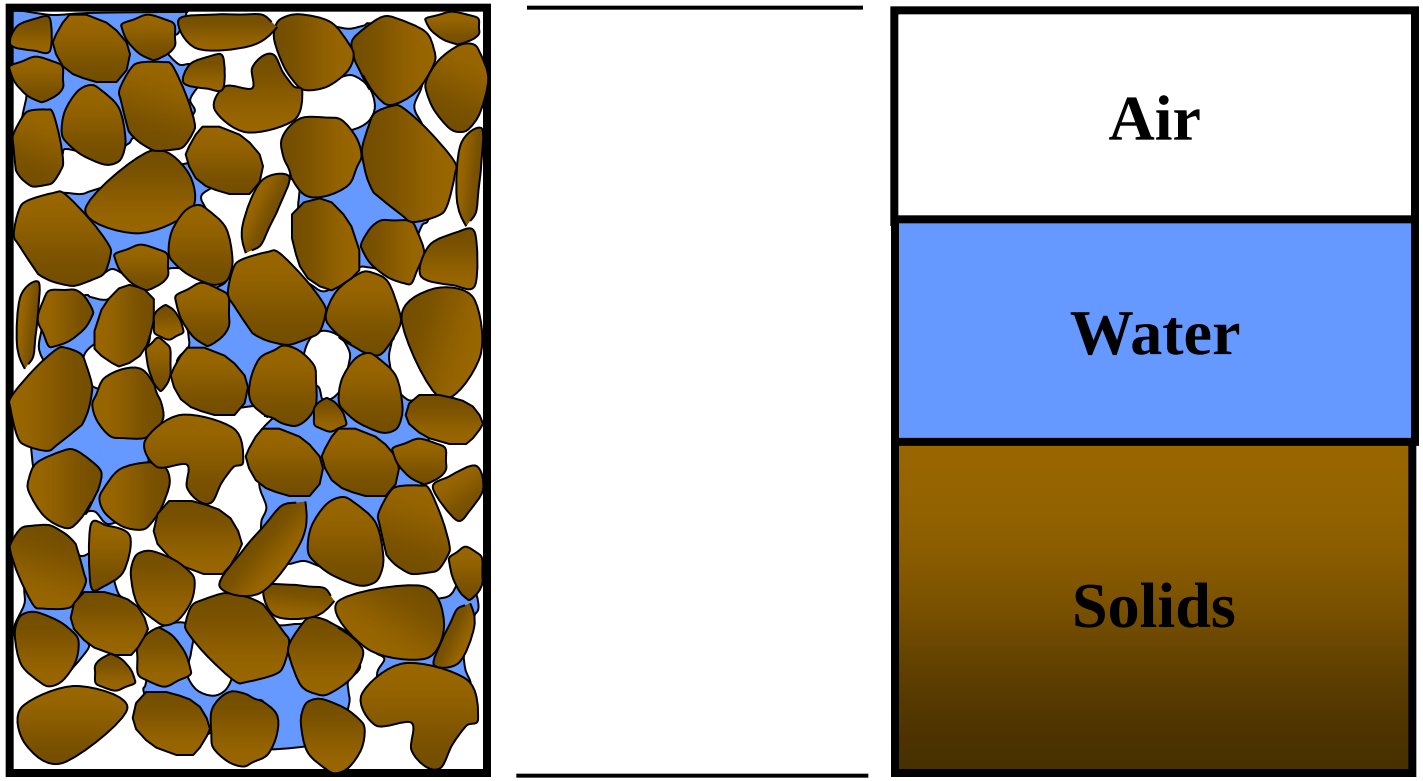
Three Phase Soil (Partially Saturated)



Mineral Skeleton

Idealization

Three Phase Diagram

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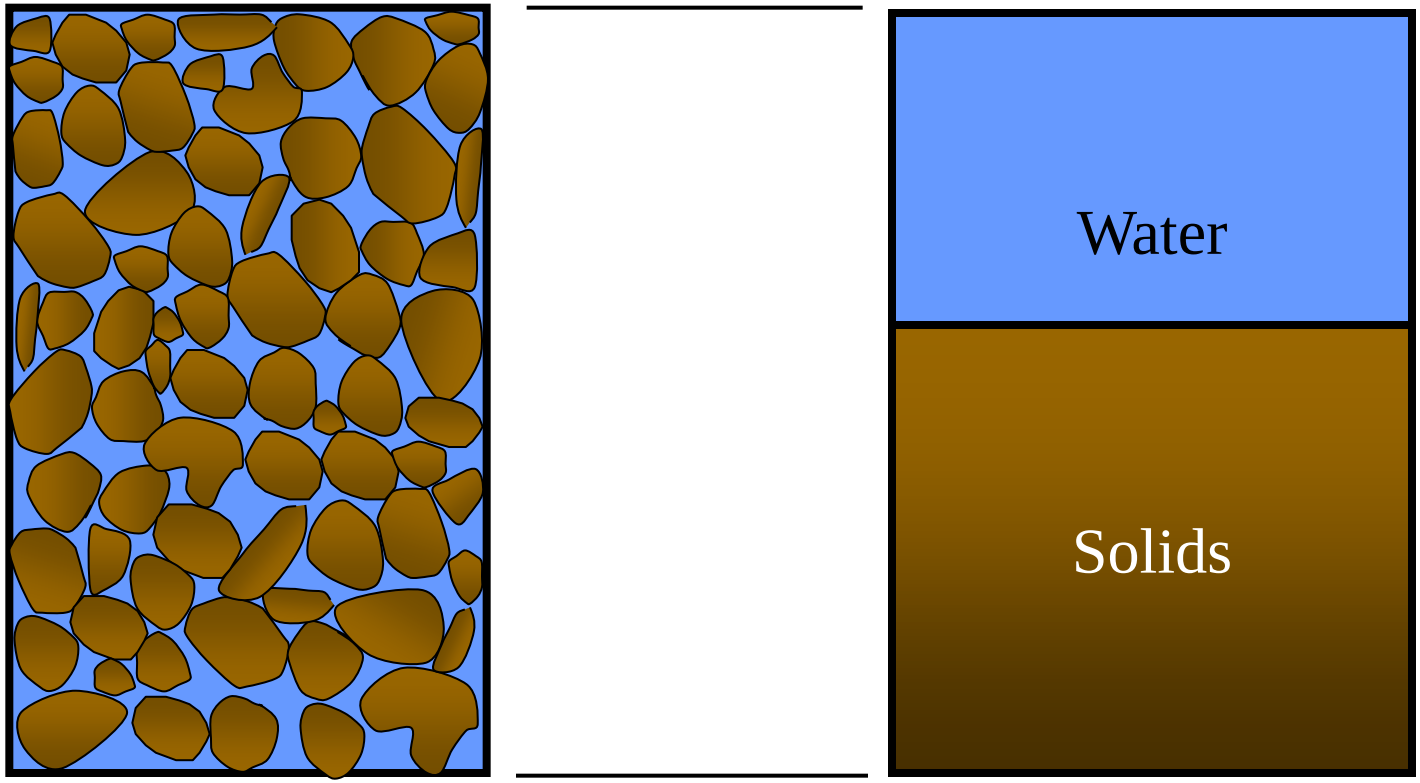
Two Phase Soil
Fully Saturated Soils



Mineral Skeleton

Fully Saturated

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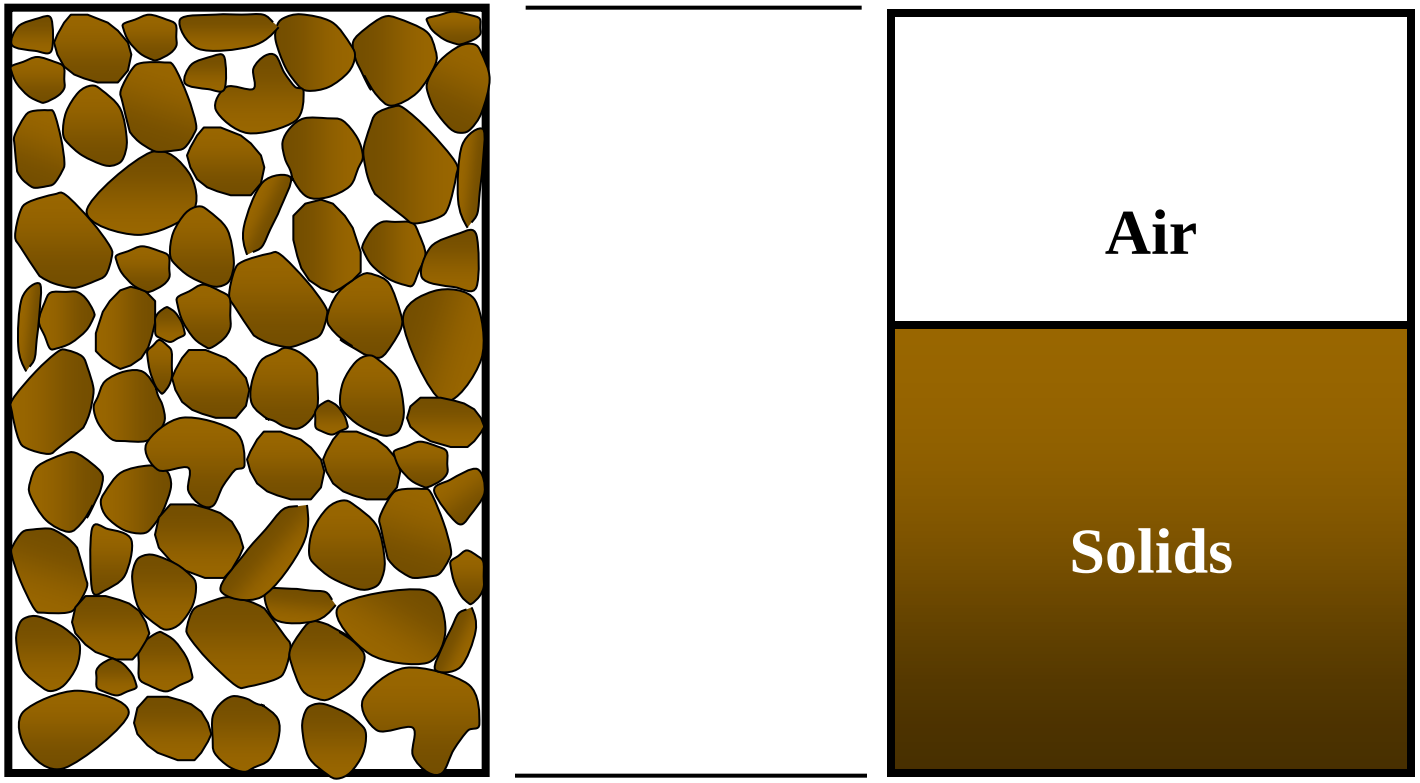
Two Phase Soil
Dry Soils [Oven Dried]



Mineral Skeleton

Dry Soil

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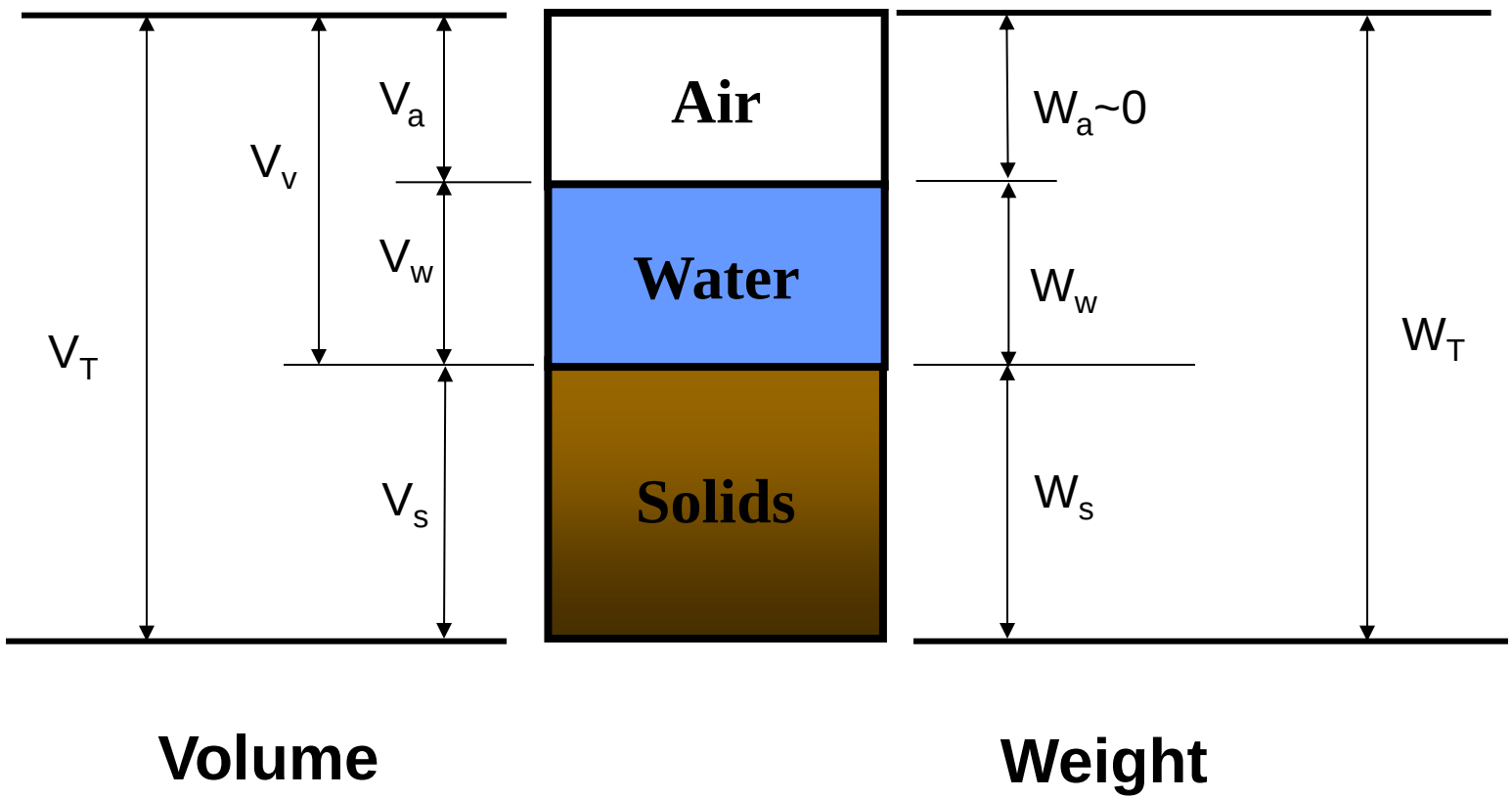
Weight-Volume Relationships



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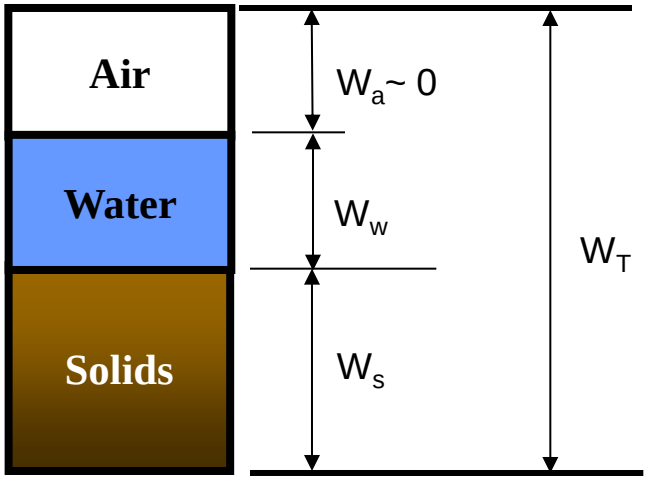
Weight Relationships (weight -ratios)

- Weight ratios
  - Moisture Content, *w*
  - Specific Gravity, G_s
- Weight Components:
  - Weight of Solids = W_s
  - Weight of Water = W_w
  - Weight of Air, $W_a \sim 0$



$$Water\ Content,\ w(\%) = \frac{W_w}{W_s} \times 100\%$$

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Specific Gravity (weight ratio)

$$Specific\,Gravity = \frac{Weight\,of\ a\ Substance}{Weight\,of\ an\,Equal\,Volume\,of\ Water}$$

$$Specific\,Gravity = \frac{Unit\,Weight\,of\ a\ Substance}{Unit\,Weight\,of\ Water}$$

$$Specific\,Gravity,\ G_s = \frac{\frac{W_s}{V_s}}{\gamma_w} = \frac{W_s}{V_s\ \gamma_w} \times 100\%$$

Unit weight of Water, γ_w or ρ_w

- γ_w = 1.0 g/cm^3 (strictly accurate at 4° C)
- γ_w = 62.4 pcf
- γ_w = 9.81 kN/m^3

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Typical Values for Specific Gravity, G_s

TABLE 4.2 SPECIFIC GRAVITY OF SELECTED NON-CLAY MINERALS

Mineral	G_s
Quartz	2.65
Feldspar	2.54 - 2.76
Hornblende	3.00 - 3.50
Mica	2.76 - 3.20
Calcite	2.71
Hematite	5.20
Limonite	3.6 - 4.0
Gypsum	2.32
Talc	2.70 - 2.80
Olivene	3.27 - 4.50

TABLE 4.3 SPECIFIC GRAVITY OF SELECTED CLAY MINERALS

Mineral	G_s
Kaolinite	2.62 - 2.66
Montmorillonite	2.75 - 2.78
Illite	2.60 - 2.86
Chlorite	2.60 - 2.96

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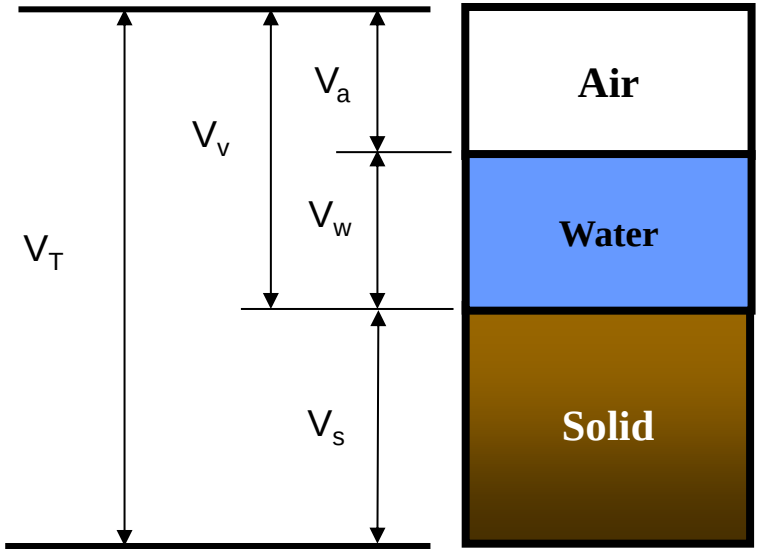
Volumetric Relationships

- <u>Volumetric ratios</u>
  - Void ratio, e
  - Porosity, n(%)
  - Degree of Saturation, S (%)

- <u>Volume Components</u>:
  - Volume of Solids = V_s
  - Volume of Water = V_w
  - Volume of Air = V_a
  - Volume of Voids = $V_a + V_w = V_v$



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Volumetric Relationships

$$Void\ Ratio,\ e = \frac{V_v}{V_s}$$

$$Porosity,\ n(\%) = \frac{V_v}{V_T} \times 100\%$$

$$Degree\ of\ Saturation,\ S(\%) = \frac{V_w}{V_V} \times 100\%$$

Weight-Volume Relationships

- Steps to develop the weight-volume relationship
  - Separate the three phases
  - The total volume of a soil

$$V = V_s + V_v = V_s + V_w + V_a$$

  - Assuming the weight of air (W_a) to be negligible, the total weight is then given as

$$W_T = W_s + W_w$$

Units

- Length meters
- Mass tonnes (1 tonne = 10^3 kg)
- Density t/m^3
- Weight kilo newtons (kN)
- Stress kilo pascals (kPa) 1 kPa= 1 kN/m^2
- Unit weight kN/m^3

- Accuracy Density of water, ρ_w = 1 t/m^3
- Stress/Strength to 0.1 kPa

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Degree of Saturation

- The degree of saturation, S, has an important influence on soil behavior
- It is defined as

$$S = \frac{V_w}{V_a + V_w} = \frac{V_w}{V_v}$$

- The phase volumes may now be expressed in terms of e, S and V_s

- $V_w = e\,S\,V_s$ $\qquad V_a = V_v - V_w = e\,Vs\,(1-S)$
- Assuming $V_s = 1m^3$, the following table can be produced

Phase	Volume	Mass	Weight
Air	e (1 - S)	0	0
Water	e S	e S ρ_w	e S γ_w
Solid	1	G_s ρ_w	G_s γ_w

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Density and Unit Weight

- Mass is a measure of a body's inertia, or its "quantity of matter". Mass is not changed at different places.
- Weight is force, the force of gravity acting on a body. The value is different at various places (Newton's second law F = ma)
- The unit weight is frequently used than the density is (e.g. in calculating the overburden pressure).

$$\text{Density, } \rho = \frac{\text{Mass}}{\text{Volume}}$$

$$\text{Unit weight, } \gamma = \frac{\text{Weight}}{\text{Volume}} = \frac{\text{Mass} \cdot g}{\text{Volume}}$$

$$g : \text{acceleration due to gravity}$$

$$\gamma = \rho \cdot g = \rho \cdot 9.8 \, {}^{m}\!/_{sec^2}$$

$$\text{Water, } \gamma = 9.8 \, {}^{kN}\!/_{m^3}$$

$$G_s = \frac{\rho_s}{\rho_w} = \frac{\rho_s \cdot g}{\rho_w \cdot g} = \frac{\gamma_s}{\gamma_w}$$

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Unit Weights

- The bulk unit weight

$$\gamma_{bulk} = \frac{W}{V} = \frac{\gamma_w G_s V_s + \gamma_w e S V_s}{V_s + e V_s} = \frac{\gamma_w (G_s + e S)}{1 + e}$$

- The saturated unit weight (S = 1)

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

- The dry unit weight (S = 0)

$$\gamma_{dry} = \frac{\gamma_w G_s}{1 + e}$$

- The submerged unit weight

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

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Moisture Content

- The moisture content, m, is defined as

$$m = \frac{Weight\ of\ Water}{Weight\ of\ Solids} = \frac{W_w}{W_s}$$

-
- In terms of e, S, G_s and γ_w
- $W_w = \gamma_w V_w = \gamma_w e S V_s$
- $W_s = \gamma_s V_s = \gamma_w G_s V_s$
-
- hence $m = \frac{e S}{G_s}$

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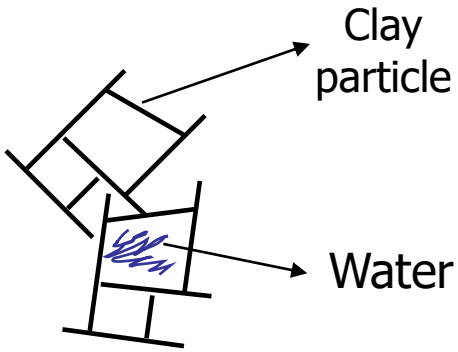
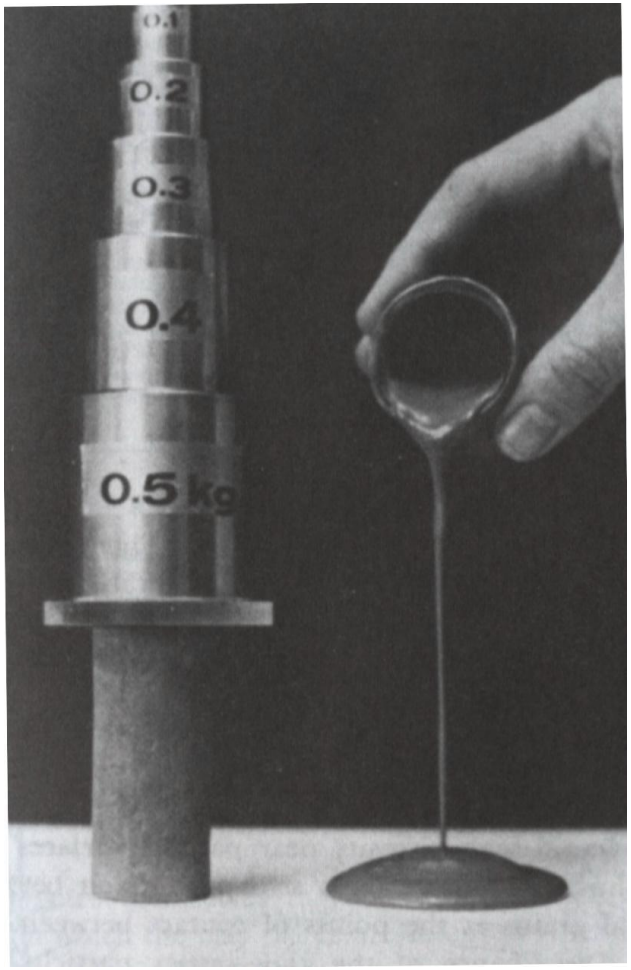
Engineering Applications (*w*)

- For fine-grained soils, water plays a critical role to their engineering properties (discussed in the next topic).
- *For example*,
- The quick clay usually has a water content *w* greater than 100 % and a card house structure. It will behave like a viscous fluid after it is fully disturbed.





(Mitchell, 1993)

Example 1

Determine void ratio, porosity, and degree of saturation based on known volume, weight, and specific gravity

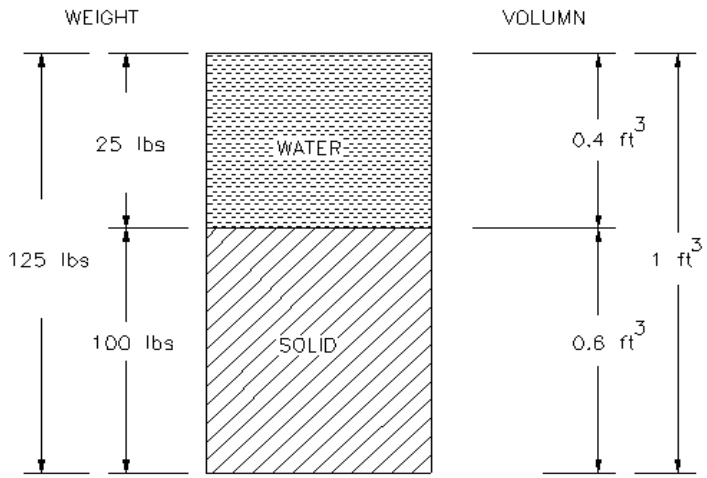
- Volume of soil mass: 0.0283 m3.
- Weight of soil mass at moist condition: 56.6 kg
- Weight of soil after dry in oven: 45.5 kg
- Specific gravity of solid = 2.65
  - **<u>Problem solving technique:</u>**
  - Void ratio, $e = Vv/Vs$ (Vv, Vs, not given)
  - Find $Vs = Ws/\gamma s$ (Ws = 45.5 kg, γs is not given)
  - Find $\gamma s = Gs\gamma w$ (Gs is given, $\gamma w = 1$ g/cm^3 is a know value)
  - Find $Vv = 1-Vs$ (e can be calculated)
  - Porosity, $n = Vv/Vt$ (Vv from step 4, Vs from step 2)
  - Degree of saturation, $S = Vw/Vv$ (Vv from step 4, need to find Vw)
  - $Vw = Ww/\gamma w$ (Ww, not given, γw=62.4 lbs/ft3)
  - Find $Ww = Wt – Ws$ (Wt = 56.6 kg, Ws = 45.5 kg are given)

Solution:

- Solid unit weight,

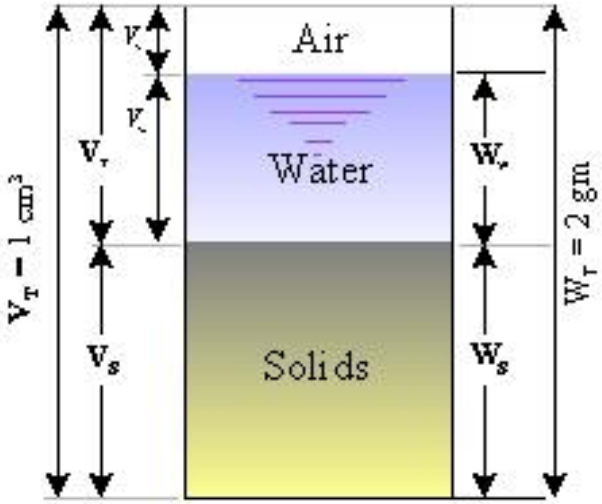
$\gamma s = Gs\gamma w = 2.65*1 = 2.65\ g/cm^3 = 2650\ kg/m^3$

- Volume of solid, $Vs = Ws/\gamma s = 45.5/2650 = 0.0171\ m^3$
- Volume of void = $Vt - Vs = 0.0283 - 0.0171 = 0.0112\ m^3$
- Void ratio, $e = Vv/Vs = 0.0112/0.0171 = 0.65$
- Porosity, $n = Vv/Vt = 0.0111/0.0283 = 0.39$
- Weight of water = 56.6-45.5=11.1 kg
- Volume of water, $Vw = Ww/\gamma w = 11.1\ kg/1\ g/cm^3 = 11100\ cm^3 = 0.0111 m^3$
- Degree of saturation, $S = Vw/Vv = 0.0111/0.0111*100\% = 100\%$.



EXAMPLE: 2

The natural moisture content, w_c, of a partially saturated soil sample was 22% and the bulk density was 2 gm/cm^3. If the specific gravity of the solid particles, G_s was 2.65 find the degree of saturation, the void ratio of the soil. If the soil is fully saturated what it would be the saturated unit weight.



Solution:

The bulk density = $\gamma_{soil} = W_T / V_T = 2 / 1$ (gm/cm^3)

$W_T = W_w + W_s = 2$ gm

$w_c = 22/100 = W_w / W_s \Rightarrow W_w = 0.22\, W_s$

$W_T = 2 = 0.22\, W_s + W_s = 1.22\, W_s$

$W_s = 2 / 1.22 = 1.64$ gm

$W_w = 2 - 1.64 = 0.36$ gm $\Rightarrow V_w = W_w / \gamma_{water} = 0.36/1 = 0.36$ cm^3

$G_s = \gamma_s / \gamma_{water} = W_s / V_s = 1.64 / V_s = 2.65$

$V_s = 0.6188$ cm^3 $\Rightarrow V_v = V_T - V_s = 1 - 0.6188 = 0.38$ cm^3

$S_r = V_w / V_v = 0.36 / 0.38 = 0.94$ or 94%

$e = V_v / V_s = 0.381 / 0.618 = 0.614$

For $\Rightarrow S_r = 100\% \Rightarrow V_v = V_w = 0.38$ cm
Therefore $W_w = V_w \cdot \gamma_{water} = 0.38$ gm
$\gamma_{soil} = W_T / V_T = (0.38 + 1.64) / 1$
$= 2.02$ gm/cm^3

- EX. 3, Distribution by mass and weight

Phase	Trimmings Mass (g)	Sample Mass, M (g)	Sample Weight, Mg (kN)
Total	55	290	2845×10^{-6}
Solid	45	237.3	2327.9×10^{-6}
Water	10	52.7	517×10^{-6}

- Distribution by volume (assume G_s = (2.65)

Total Volume $V = \pi r^2 l = 29.75$

Water Volume $$V_w = \frac{W_w}{\gamma_w}$$

Solids Volume $$V_s = \frac{W_s}{\gamma_w G_s}$$

Air Volume $V_a = V - V_s - V_w$

- Moisture content $m = \frac{W_w}{W_s} = \frac{10}{45} = 0.222 = 22.2\,\%$
- Voids ratio $e = \frac{V_v}{V_s} = \frac{V_a + V_w}{V_s} = 0.755$
- Degree of Saturation $S = \frac{V_w}{V_v} = \frac{V_w}{V_a + V_w} = 0.780 = 78.0\,\%$
- Bulk unit weight $\gamma_{bulk} = \frac{W}{V} = 18.1\,kN/m^3$
- Dry unit weight $\gamma_{dry} = \frac{W_s}{V} = 14.8\,kN/m^3$
- Saturated unit weight $\gamma_{sat} = \frac{(W + 14.9 \times 10^{-6} \times 9.81)}{V} = 19.04\,kN/m^3$

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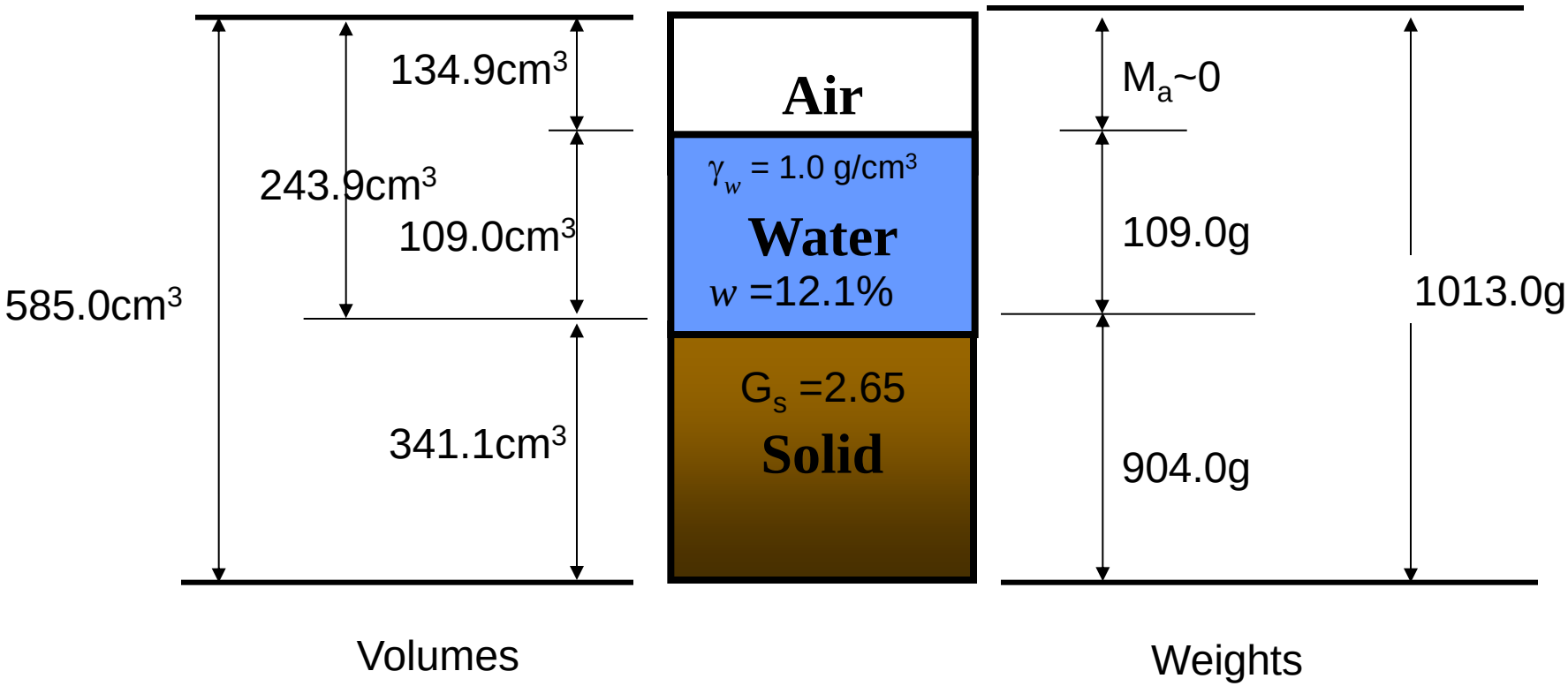
Example 4

Weight of soil sample, MT = 1013g
Vol. of soil sample, VT = 585.0cm3
Specific Gravity, Gs = 2.65
Moisture Content, w = 12.1%



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Example4

1

$$M_T = M_w + M_s \quad \ldots(1)$$

$$but \quad w = \frac{M_w}{M_s} \Rightarrow M_w = w M_s \quad \ldots(2)$$

$$substitute \quad (2) \quad in \quad (1)$$

$$M_T = w M_s + M_s = (1+w) M_s$$

$$\Rightarrow M_s = \frac{M_T}{1+w} = \frac{1013}{1+0.121} \approx 904g$$

2

$$M_w = M_T - M_s = 1013 - 904 = 109g$$

3

$$\gamma_w = \frac{W_w}{V_w} \Rightarrow V_w = \frac{W_w}{\gamma_w} = \frac{109(g)}{1.0(g/cm^3)} = 109cm^3$$

4

$$G_s = \frac{W_s}{V_s \gamma_w} \Rightarrow V_s = \frac{W_s}{G_s \gamma_w} = \frac{904(g)}{2.65 \times 1.0(g/cm^3)} = 341.1cm^3$$

5

$$V_a = V_T - (V_s + V_w) = 585 - (341.1 + 109) = 134.9cm^3$$

6

$$V_v = V_w + V_a = 109 + 134.9 = 243.9g$$

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Weight-Volume Relationships

- From the previous figure we can find:
  - Moisture content, *w*
  - Void ratio, *e*
  - Porosity, *n*
  - Degree of saturation, *S*
  - Dry unit weight, γ_d

$$w = \frac{W_w}{W_s} = \frac{109(g)}{904(g)} \times 100 = 12.1\%$$

$$e = \frac{V_v}{V_s} = \frac{243.9cm^3}{341.1cm^3} = 0.715$$

$$n = \frac{V_v}{V_T} = \frac{243.9\ (cm^3)}{585.0\ (cm^3)} \times 100 = 41.7\%$$

$$S = \frac{V_w}{V_v} = \frac{109}{243.9} \times 100 = 44.7\%$$

$$\gamma_d = \frac{W_s}{V_T} = \frac{904}{585} = 1.55\frac{g}{cm^3}$$

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Weight-Volume Relationships

Table 3.1 Various Forms of Relationships for γ, γ_d, and γ_{sat}

Moist unit weight (γ)		***Dry unit weight*** (γ_d)		***Saturated unit weight*** (γ_{sat})	
Given	**Relationship**	**Given**	**Relationship**	**Given**	**Relationship**
w, G_s, e	$\dfrac{(1+w)G_s\gamma_w}{1+e}$	γ, w	$\dfrac{\gamma}{1+w}$	G_s, e	$\dfrac{(G_s+e)\gamma_w}{1+e}$
S, G_s, e	$\dfrac{(G_s+Se)\gamma_w}{1+e}$	G_s, e	$\dfrac{G_s\gamma_w}{1+e}$	G_s, n	$[(1-n)G_s+n]\gamma_w$
w, G_s, S	$\dfrac{(1+w)G_s\gamma_w}{1+\dfrac{wG_s}{S}}$	G_s, n	$G_s\gamma_w(1-n)$	G_s, w_{sat}	$\left(\dfrac{1+w_{sat}}{1+w_{sat}G_s}\right)G_s\gamma_w$
w, G_s, n	$G_s\gamma_w(1-n)(1+w)$	G_s, w, S	$\dfrac{G_s\gamma_w}{1+\left(\dfrac{wG_s}{S}\right)}$	e, w_{sat}	$\left(\dfrac{e}{w_{sat}}\right)\left(\dfrac{1+w_{sat}}{1+e}\right)\gamma_w$
S, G_s, n	$G_s\gamma_w(1-n)+nS\gamma_w$	e, w, S	$\dfrac{eS\gamma_w}{(1+e)w}$	n, w_{sat}	$n\left(\dfrac{1+w_{sat}}{w_{sat}}\right)\gamma_w$
		γ_{sat}, e	$\gamma_{sat}-\dfrac{e\gamma_w}{1+e}$	γ_d, e	$\gamma_d+\left(\dfrac{e}{1+e}\right)\gamma_w$
		γ_{sat}, n	$\gamma_{sat}-n\gamma_w$	γ_d, n	$\gamma_d+n\gamma_w$
		γ_{sat}, G_s	$\dfrac{(\gamma_{sat}-\gamma_w)G_s}{(G_s-1)}$	γ_d, S	$\left(1-\dfrac{1}{G_s}\right)\gamma_d+\gamma_w$
				γ_d, w_{sat}	$\gamma_d(1+w_{sat})$

Example 3.1

In the natural state, a moist soil has a volume of 0.0093 m³ and weighs 177.6 N. The oven dry weight of the soil is 153.6 N. If $G_s = 2.71$, calculate the moisture content, moist unit weight, dry unit weight, void ratio, porosity, and degree of saturation.

Solution

Refer to Figure 3.6. The moisture content [Eq. (3.8)] is

$$w = \frac{W_w}{W_s} = \frac{W - W_s}{W_s} = \frac{177.6 - 153.6}{153.6} = \frac{24}{153.6} \times 100 = \mathbf{15.6\%}$$

The moist unit weight [Eq. (3.9)] is

$$\gamma = \frac{W}{V} = \frac{177.6}{0.0093} = 19{,}096 \text{ N/m}^3 \approx \mathbf{19.1\ kN/m^3}$$

For dry unit weight [Eq. (3.11)], we have

$$\gamma_d = \frac{W_s}{V} = \frac{153.6}{0.0093} = 16{,}516 \text{ N/m}^3 \approx \mathbf{16.52\ kN/m^3}$$

The void ratio [Eq. (3.3)] is found as follows:

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

$$V_s = \frac{W_s}{G_s \gamma_w} = \frac{0.1536}{2.71 \times 9.81} = 0.0058 \text{ m}^3$$

$$V_v = V - V_s = 0.0093 - 0.0058 = 0.0035 \text{ m}^3$$

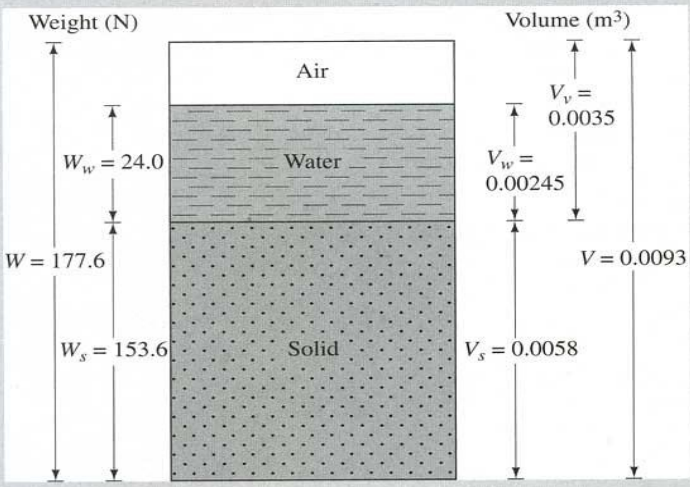

Figure 3.6

so

$$e = \frac{0.0035}{0.0058} \approx \mathbf{0.60}$$

For porosity [Eq. (3.7)], we have

$$n = \frac{e}{1+e} = \frac{0.60}{1+0.60} = \mathbf{0.375}$$

We find the degree of saturation [Eq. (3.5)] as follows:

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

$$V_w = \frac{W_w}{\gamma_w} = \frac{0.024}{9.81} = 0.00245 \text{ m}^3$$

so

$$S = \frac{0.00245}{0.0035} \times 100 = \mathbf{70\%}$$

■

The End