University of Anbar
College of Engineering

Soil Mechanics

Prepared
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Civil Engineering Department

RAMADI – IRAQ

College of Engineering

COURSE SYLLABUS

Course Title

SOIL MECHANICS

Course Code

CE 3321

2nd (Spring) Semester, 2018 / 2019

Course descritption:

This course introduces the students to the Fundamental engineering properties of soil and their applications in geotechnical engineering This course covers the following topics:-

Soil composition, physical and chemical properties, and classifications; water movement and seepage problems; effective stress concept, stress distribution in soil mass, consolidation, shear strength, compaction and soil improvement.

Course Objectives/Goals:

The goals of this course are to enable students:

1. To develop an appreciation soil as a vital construction material, and of soil mechanics in the engineering of civil infrastructure;
2. To develop an understanding of the relationships between physical characteristics and mechanical properties of soils;
3. To understand the concepts governing the mechanical and fluid transport properties of soils
4. To understand and be able to apply the modeling and analysis techniques used in soil mechanics: (a) Darcy's Law and flow-nets for seepage; (b) consolidation models for load-time-deformation responses of soils; (c) Mohr-Coulomb models for shear strength behavior of soils.

Course Learning Outcomes:

By the end of successful completion of this course, the student will be able to:

1. understand the origin, formation, parameters and basic fundamental behavior of soils and have the knowledge of soil classification and be able to classify the soil using Unified Soil Classification System
2. understand the principles of soil compaction and the factors affecting soil compaction
3. understand soil permeability and seepage theory and be able to analyze a seepage problem by flow net
4. understand the effective stress concept and be able to calculate effective stress in non-seepage and seepage problems and be able to calculate the vertical stress in soils caused by various types of loading
5. apply one-dimensional consolidation theory to calculate settlement and pore pressure as a function of time during consolidation
6. apply the principles of shear strength of soils to various laboratory tests

Distribution of Course Topics/Contents

Topics Covered	Chapter in Textbook	CLO
ORIGIN OF SOIL AND GRAIN SIZE	Chapter 2	1
WEIGHT-VOLUME RELATIONSHIPS, PLASTICIY, AND STRUCTURE OF SOIL	Chapter 3	1
ENGINEERING CLASSIFICATION OF SOIL	Chapter 3	1
PERMEABILITY AND SEEPAGE PERMEABILITY	Chapter 5	3
IN SITU STRESSES	Chapter 6	4
STRESSES IN SOIL MASS	Chapter 6	4
CONSOLIDATIOM OF SOIL	Chapter 7	5
SHEAR STRENGTH OF SOIL	Chapter 8	6
SOIL COMPACTION	Chapter 4	2

Teaching and Learning Resources:

Text Book(s):

Braja M. Das, Fundamentals of Geotechnical Engineering, Cengage Learning, 3rd ed., 2008

Recommended Readings:

1. **Principles of geotechnical engineering, Braja M. Das, 8th edition**
2. **Soil mechanics, R.F. Craig, 8th ed.**
3. **Solving problems in soil mechanics, B.H.C. Sutton, 2nd ed.**

Students' Assessment:

Students are assessed as follows:

Assessment Tool(s)**	**Date**	**Weight (%)**
Semester activities: These include, Homeworks	At the end of each major topic	**15%**
Mid semester exam **or** Progress Exams	According to department schedule	**25%**
Final Exam	Week-16	**60%**
Total		**100%**

Estimated Content	**3 credit**
Math.	**20%**
Engineering Science	**80%**
Engineering Design	**0%**

Soil Mechanics

Assistant Professor Dr. Khalid R. Mahmood, Instructor

Catalogue Description

- *Origin of Soil and Grain Size*
- *Weight-Volume Relationships, Plasticity, and Structure of Soil*
- *Engineering Classification of Soil*
- *Permeability*
- *Seepage*
- *In Situ Stresses (Effective Stress Concept)*
- *Stresses in a Soil Mass*
- *Compressibility of Soil*
- *Shear Strength of Soil*
- *Soil Compaction*

Textbook and Reference Books

Textbook- Fundamentals of Geotechnical Engineering, Braja M. Das, 3rd ed., 2008

1. *Principles of geotechnical engineering, Braja M. Das, 8th edition*
2. *Soil mechanics, R.F. Craig, 8th ed.*
3. *Solving problems in soil mechanics, B.H.C. Sutton, 2nd ed.*
4. *Soil mechanics laboratory manual, Braja M. Das, 6th ed., 2002*

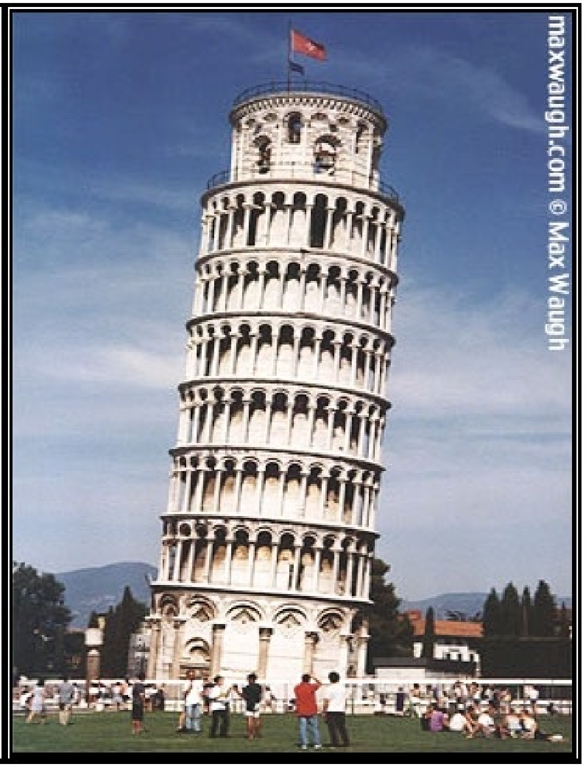
Types of Civil Engineering

- Structural Engineering
- Transportation Engineering
- Environmental Engineering
- Coastal Engineering
- **Geotechnical Engineering** → **Soil Mechanics**, **Foundation Engineering**

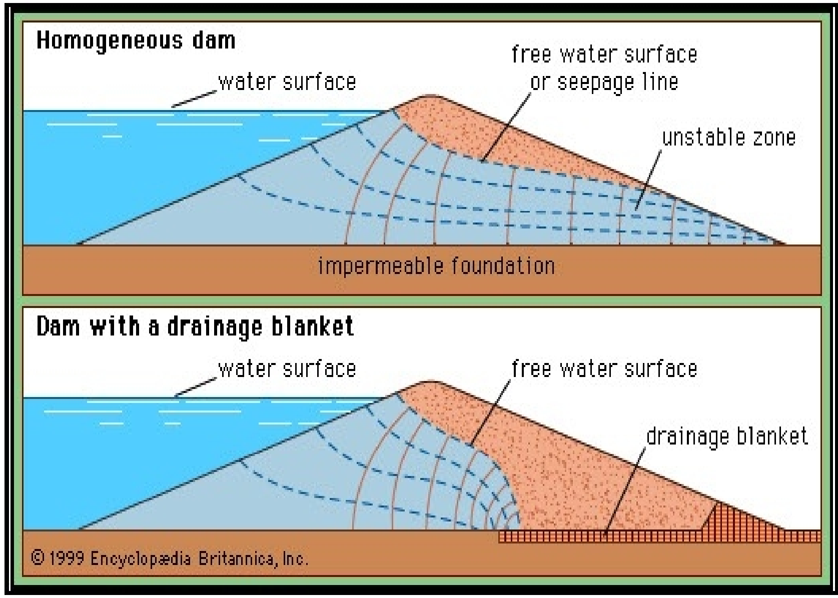
Problems in Geotechnical Engineering

- Shear Failure-Loads have exceeded shear strength capacity of soil!

- Settlement

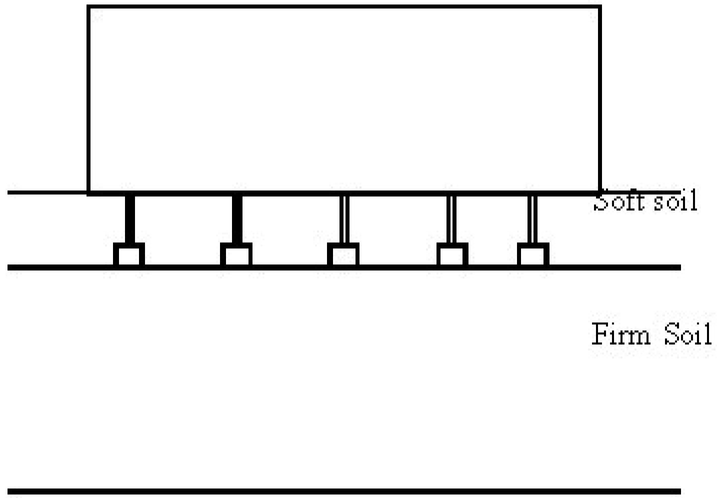


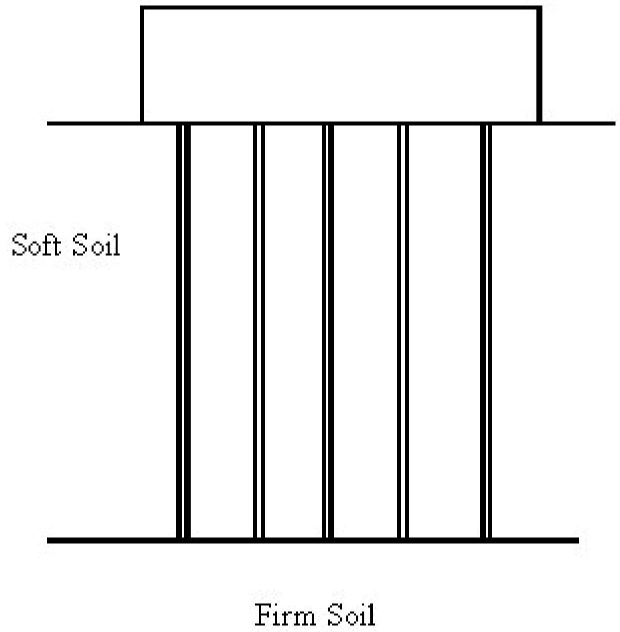
• Seepage Problems



Engineering problems related to Soil Mechanics

1- Soil as a foundation





For difficult soil condition such as **expansive soil**, **collapsible soil (gypseous soil)** special precautions must be taken in designing and construction of foundations on such soils.

2- Soil as a construction material

It can be used in works such as:

- Pavement works (Flexible and Rigid pavements works)
- Earth dams and embankments
- Earth filling.

Here we must take into consideration the following factors

- Type of soil to be selected.
- Quality control of compacting soil.
- Proper methods are used for replacement and compaction of the soil.
- The availability of the required type of soil near the site.

The Unique Nature of Soil

The soils are often highly variable, even within a distance of few millimeters. Another way of saying this is that soils are-

- **Heterogeneous** rather than **homogenous** materials.
- **Anisotropic** instead of being **Isotropic**
- The stress-strain relationships did not obey linear stress- strain laws.
- their behavior depends on pressure, time, and the environment.

Most of the theories we have for the mechanical behavior of engineering materials assume that the materials are Homogenous, Isotropic and obey linear stress- strain laws, so most of the relations used in Soil Mechanics are empirical relationships.

The solution of soil engineering problems

It includes the basic principles of-

Soil mechanics

Geology, Exploration

Experience

Economics

} + Engineering Judgment = Solutions

Origin of Soil and Grain Size

Soils and Rocks

Definition of "Soil" and "Rock"

● **Soil**

Naturally occurring mineral particles which are readily separated into relatively small pieces, and in which the mass may contain air, water, or organic materials (derived from the decay of vegetation).

● **Rock**

Naturally occurring material composed of mineral particles so firmly bonded together that relatively great effort is required to separate the particles (i.e., blasting or heavy crushing forces).

Types of Rocks

● Igneous rocks (**Intrusive** and **extrusive**) such as Granite, Basalt, ….etc.
● Sedimentary rocks such as sandstone, limestone, shales,….etc.
● Metamorphic rocks such as gneiss, marble, slate

Methods of Classifying Rocks

- Visual Classification
- Weathering Classification
- Discontinuity Classification
- Colour and Grain Size
- Hardness Classification
- Geological Classification
- Classification by Field Measurements and Strength Tests
- Strength
- Rock Quality Designation and Velocity Index Rock

Rock Quality Designation (RQD)

- Based on a modified core recovery procedure

  L_i = length of a given recovered piece ≥ 4"

  L_t = total length of core sample

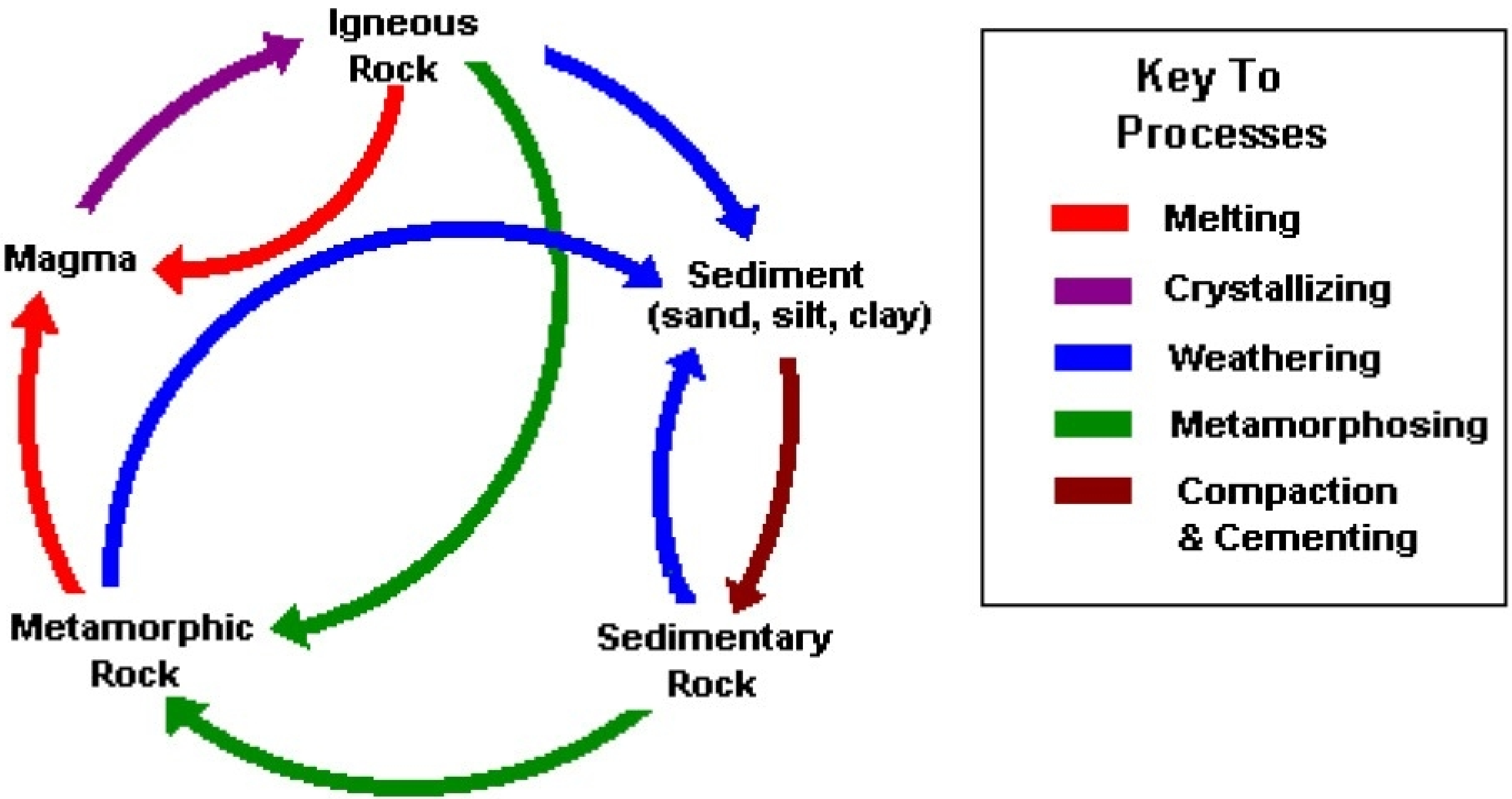
$$RQD = \frac{\sum L_i}{L_t}$$

- Velocity index
  - Square of the ratio of the field compression wave velocity to the laboratory compression wave velocity
  - Typically used to determine rock quality using geophysical surveys

Rock Quality Designation (RQD)

RQD%	VELOCITY INDEX	ROCK MASS QUALITY
90 - 100	0.80 - 1.00	Excellent
75 - 90	0.60 - 0.80	Good
50 - 75	0.40 - 0.60	Fair
25 - 50	0.20 - 0.40	Poor
0 - 25	0 - 0.20	Very Poor

Soil – Rock Cycle



Weathering

Physical or Mechanical weathering causes disintegration of the rocks into smaller particle sizes, the processes that cause physical weathering are-

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

Chemical weathering causes decomposition in rocks by –

- **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**

Basic Soil Types

<table>
<tr><th colspan="3">Parent Rocks</th></tr>
<tr><th rowspan="2">Sedimentary Soils</th><th colspan="2">Transported Soils</th></tr>
<tr><th></th><th>transported and deposited by</th></tr>
<tr><td>• Residual
• Organic</td><td>• Alluvial
• Aeolian
• Glacial
• Marine
• Colluvial
• Pyroclastic</td><td>running water
wind
glaciers, or by melt water from the glacier
ocean waves and currents in shore and offshore
gravity
Material-propelled lava</td></tr>
</table>

Special Soils (problematic soil)

- Expansive Soils
- Collapsing Soils
- Permafrost and Frost Penetration
- Man-made and Hydraulic Fills
- Limestone and Related Soils
- Karst Topography
- Calcareous Soils
- Quick Clays
- Dispersive Clays
- Submarine Soils

Soil-Particle Size or Grain Sizes

We are often interested in the particle or grain sizes present in a particular soil as well as the distribution of those sizes.

Its range

Boulders or cobbles ⟷ **Ultra fine – grained colloidal materials**

D > 75 mm **10^8 max. log scale** **D < 0.001 mm**

Table 2.1 Soil-separate-size limits

	Cohesionless soils		*Cohesive soils*	
	Grain size (mm)			
Name of organization	**Gravel**	**Sand**	**Silt**	**Clay**
Massachusetts Institute of Technology (MIT)	>2	2 to 0.06	0.06 to 0.002	<0.002
U.S. Department of Agriculture (USDA)	>2	2 to 0.05	0.05 to 0.002	<0.002
American Association of State Highway and Transportation Officials (AASHTO)	76.2 to 2	2 to 0.075	0.075 to 0.002	<0.002
Unified Soil Classification System (U.S. Army Corps of Engineers; U.S. Bureau of Reclamation; American Society for Testing and Materials)	76.2 to 4.75	4.75 to 0.075	Fines (i.e., silts and clays) <0.075	

Soil Cohesion

Coarse-grained, Granular or Cohesionless Soils	*Fine-Grained or Cohesive Soils*
•Generally are granular or coarse-grained •Particles do not naturally adhere to each other •Have higher permeability •Excellent foundation material for supporting structures and roads. •The best embankment material. •The best backfill material for retaining walls. •Might settle under vibratory loads or blasts. •Dewatering can be difficult due to high permeability. •If free draining does not frost susceptible	• Generally are fine grained • Particles have natural adhesion to each other • due to the presence of clay minerals • Have low permeability • Very often, possess low shear strength. • Plastic and compressible. • Loses part of shear strength upon wetting. • Loses part of shear strength upon disturbance. • Shrinks upon drying and expands upon wetting. • Very poor material for backfill. • Poor material for embankments. • Practically impervious. • Clay slopes are prone to landslides.

Silts

• Characteristics	Compared to Clays
• Relatively low shear strength	• Better load sustaining qualities
• High Capillarity and frost susceptibility	• Less compressible
• Relatively low permeability	• More permeable
• Difficult to compact	• Exhibit less volume change

Aspects of Cohesionless Soils

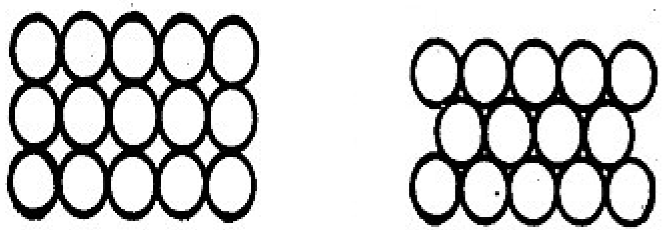
Angularity

- Angular – Sharp Edges
- Subangular – Edges distinct but well rounded
- Subrounded
- Rounded
- Well Rounded

Density

- Both unit weight and strength of soil can vary with particle arrangement
- Denser soils have both higher load carrying capacity and lower settlement

$$e_{max} = 0.91 \qquad n_{max} = 48\%$$
$$e_{min} = 0.35 \qquad n_{min} = 26\%$$



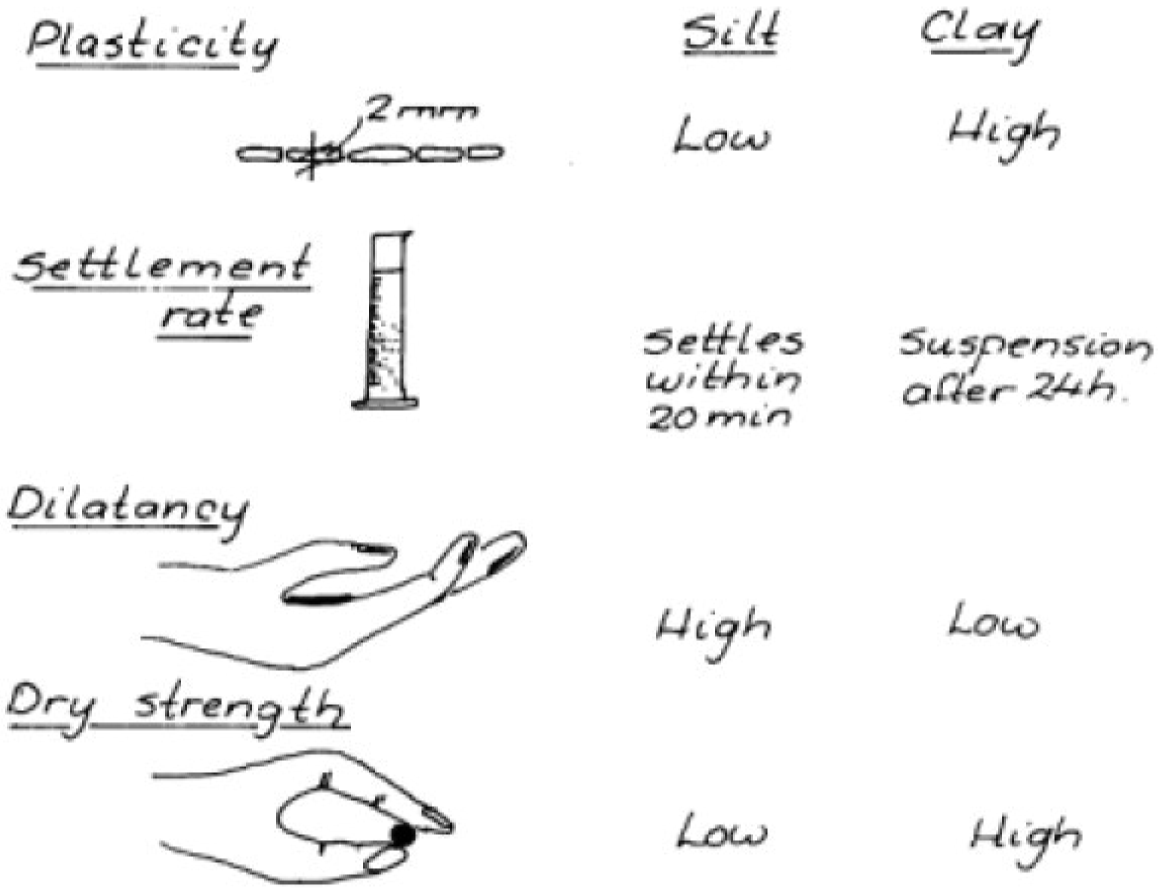
(I) (II)

Relative Density

$$D_r = \frac{e_{max} - e_o}{e_{max} - e_{min}} x100$$

- e_{max} = void ratio of the soil in its loosest condition
- e_{min} = void ratio of the soil in its densest condition
- e_0 = void ratio in the natural or condition of interest of the soil
- Convenient measure for the strength of a cohesionless soil

Properties of Fine Soils



	Silt	Clay
Plasticity (2 mm)	Low	High
Settlement rate	Settles within 20 min	Suspension after 24h.
Dilatancy	High	Low
Dry strength	Low	High

Aspects of Cohesive and Fine-Grained Soils

- Structure of Clay Minerals
- Types of Clay Minerals
- Clay Minerals and Water
- Particle Orientation of Clay Soils
- Thixotropy

Structure of Clay Minerals

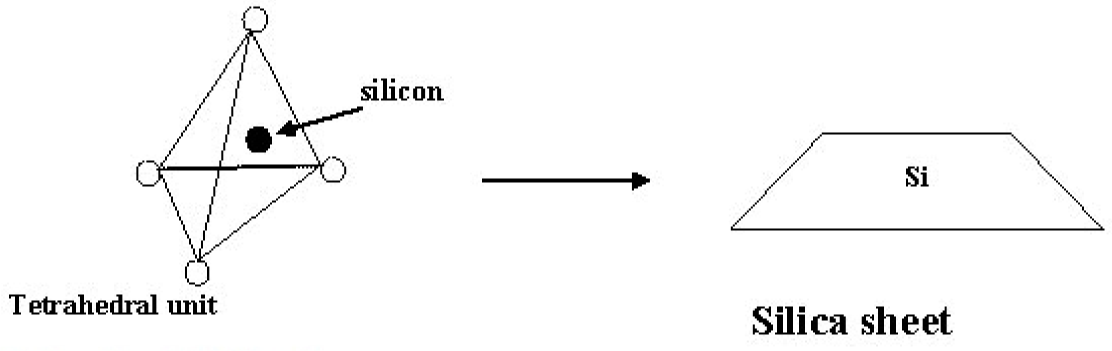
Clay minerals are very tiny crystalline substances evolved primarily from chemical weathering of certain rock forming minerals, they are ***complex alumino – silicates plus other metallic ions.***

All clay minerals are very small with colloidal – sized (D < 1μm). Because of their small size and flat shape, they have very large specific surfaces.

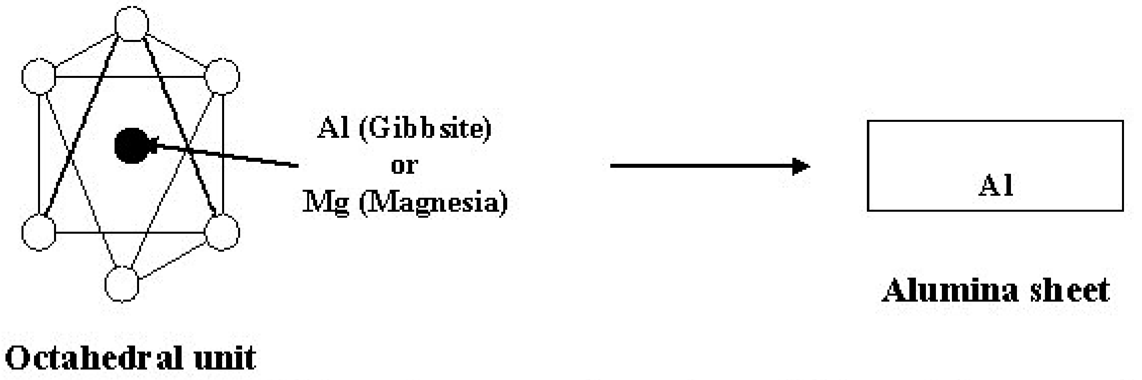
There is usually a negative electric charge on the crystal surfaces and electro – chemical forces on these surfaces are therefore predominant in determining their engineering properties.

In order to understand why these materials behave as they do, it will be necessary to examine their crystal structure in some detail.

- Atoms of clay minerals form sheets
  - **Silica tetrahedral sheets**



  - **Alumina octahedral sheets**



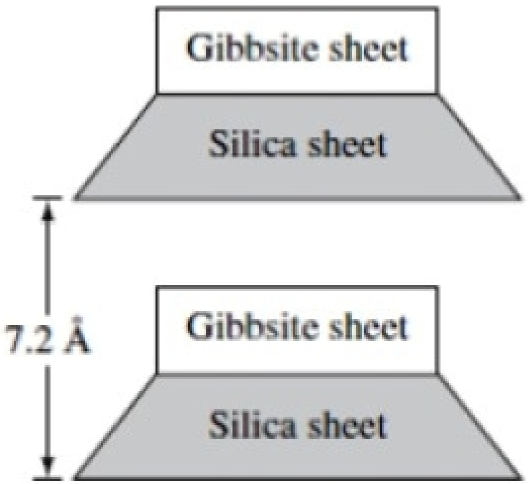
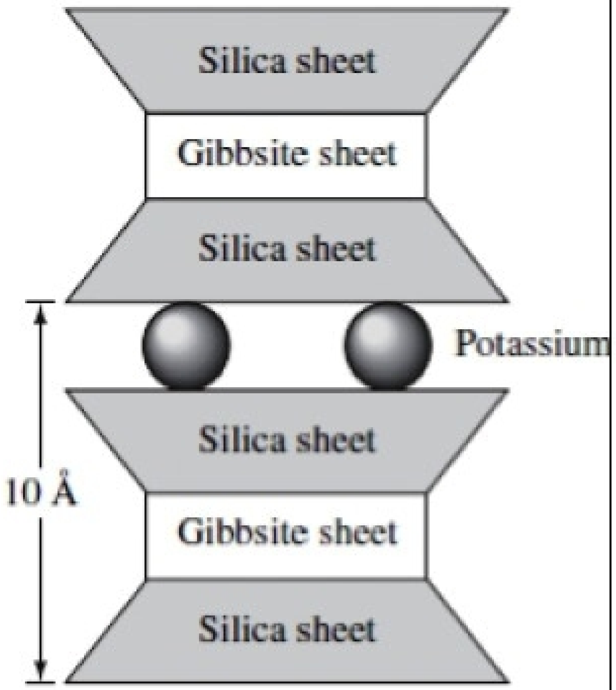
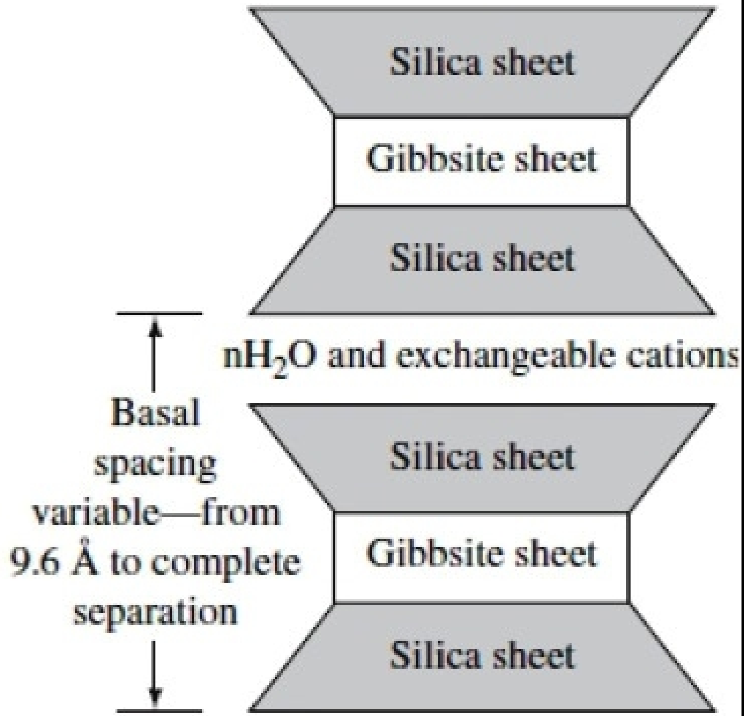
- Sheets can layer in different ways, forming different types of clay minerals
- Clay minerals tend to form flat, platelike, and niddle shapes

- **Electro – Chemical Forces**
  - Primary valency bonds
  - Van der Waals forces or molecular bonds
  - Polar forces
  - Hydrogen bonds

- **Isomorphic substitutions and absorbed ions**

  It is the replacement of the silicon and aluminum ions in the crystal by other elements, with no change in the crystalline structure

Types of Clay Minerals

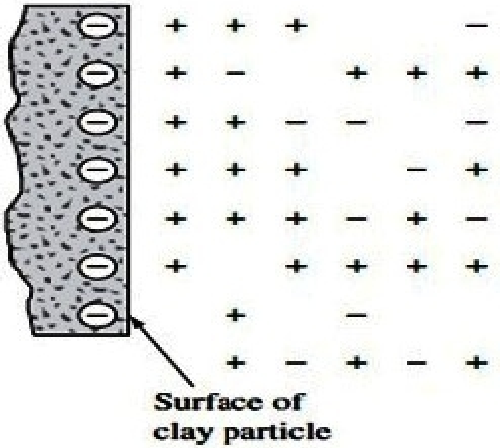
Kaolinite group	*Illite group*	*Montmorillonite group*
	 (b)	

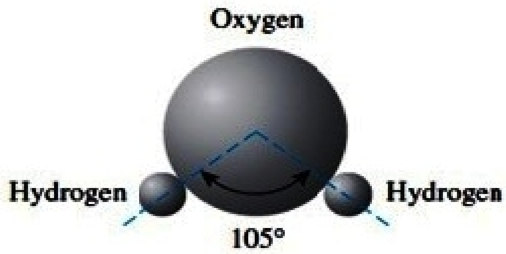
Specific surface

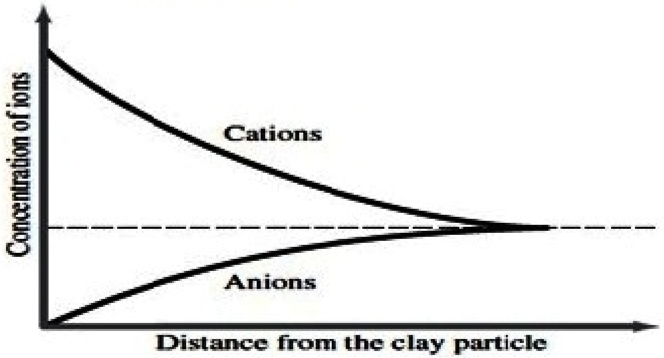
$$S.S = \frac{As}{V} \left(\frac{1}{length}\right) \quad ; \quad S.S = \frac{As}{m} \left(\frac{length^2}{mass}\right)$$

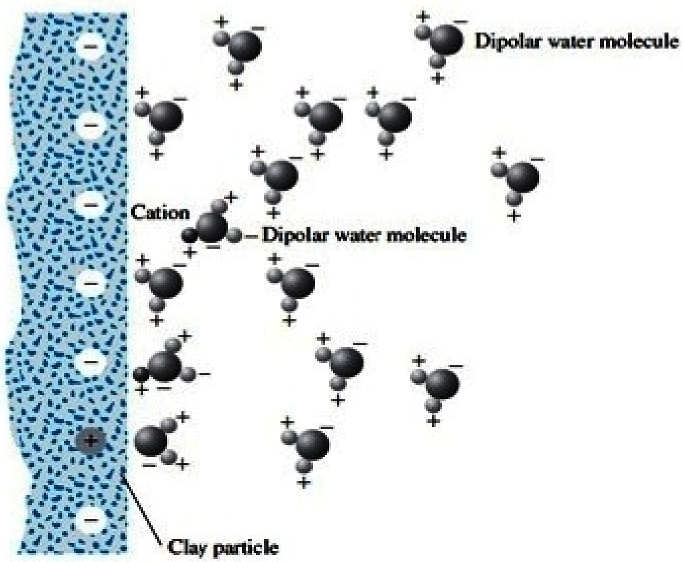
Cube	S.S
1x1x1 cm^3	$\frac{6(1cm^2)}{1cm^3} = 6/cm = 0.6/mm$
1x1x1 mm^3	$\frac{6(1mm^2)}{1mm^3} = 6/mm$
1x1x1 μm^3	$\frac{6(1\mu m^2)}{1\mu m^3} = 6/\mu m = 6000/mm$

How is water absorbed on the surface of a clay particle?



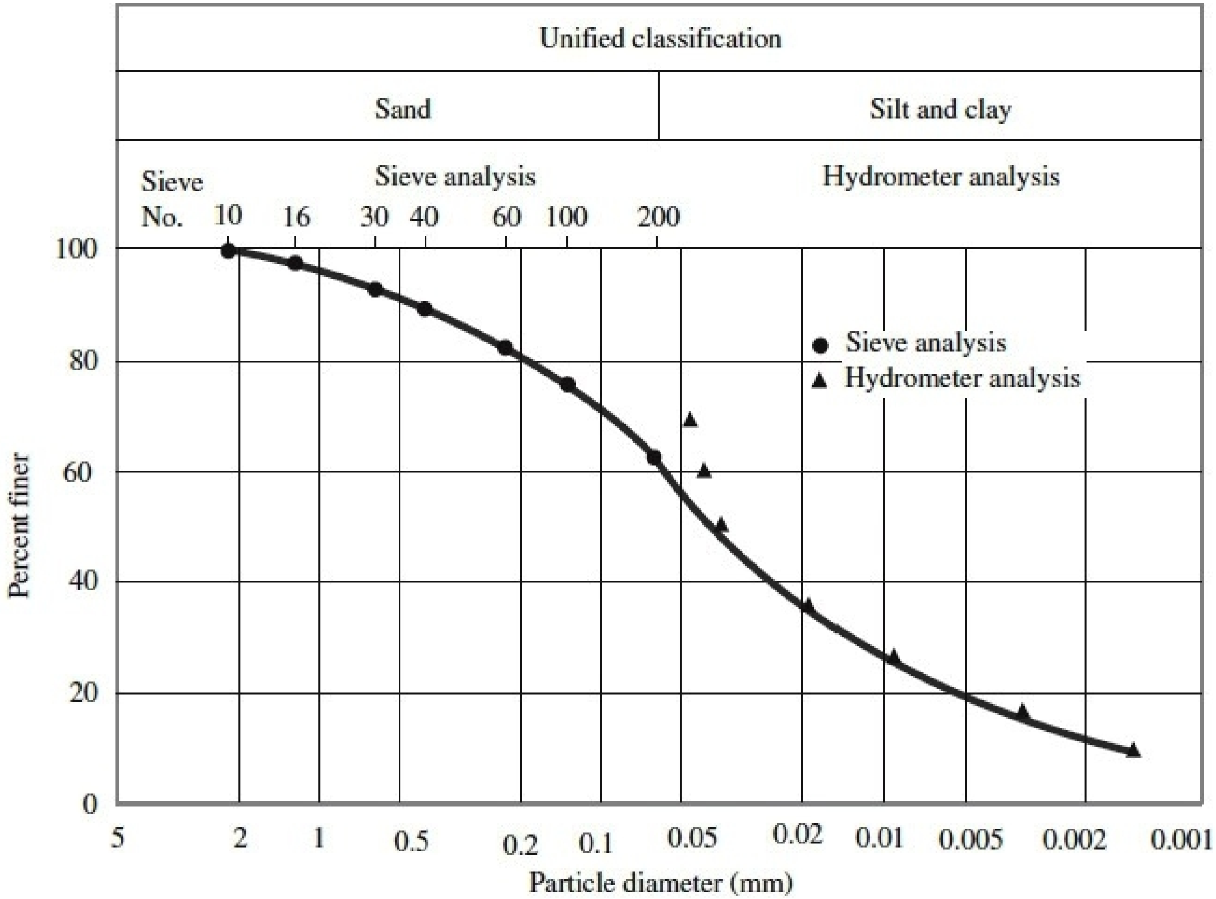


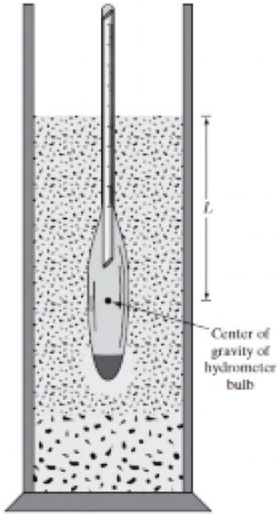




Gradation of Particle Size

Sieve Analysis
Hydrometer Analysis




L
Center of gravity of hydrometer bulb

Dx – designates particle size for which x percent of sample has passed

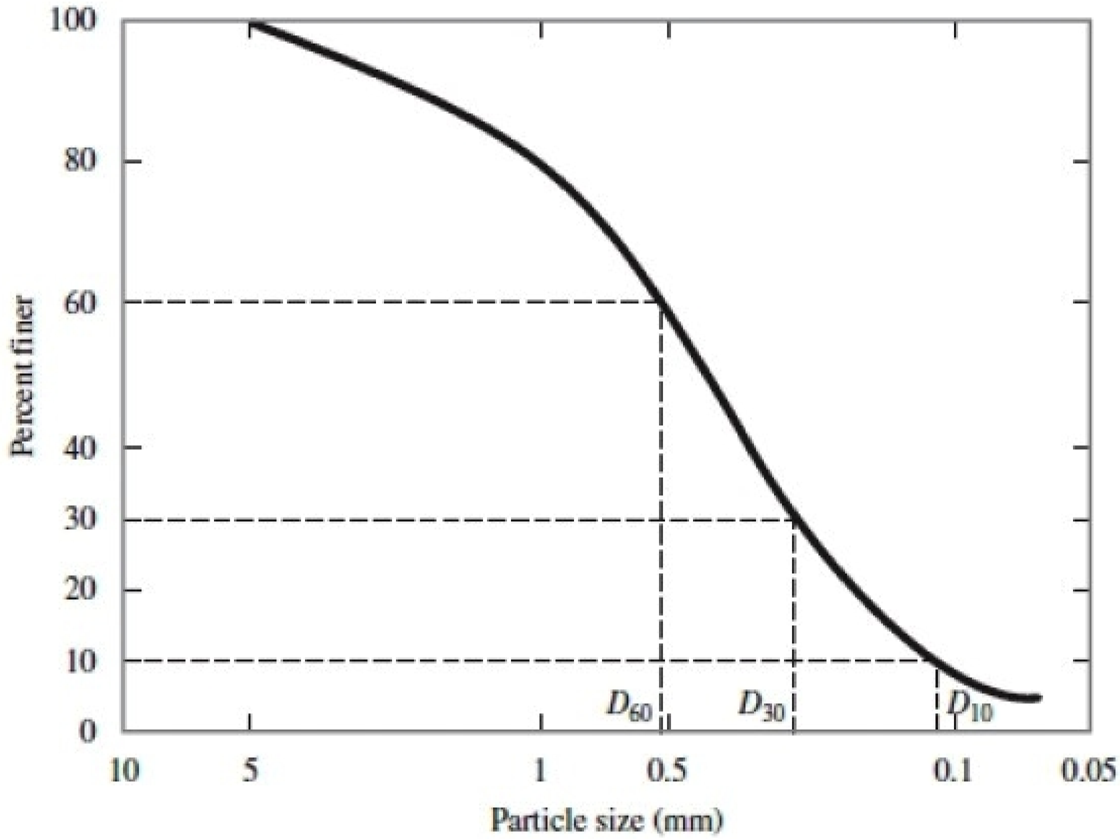
- D_{10} – effective size – particle size at which 10% of the sample has passed. It is useful to determine permeability

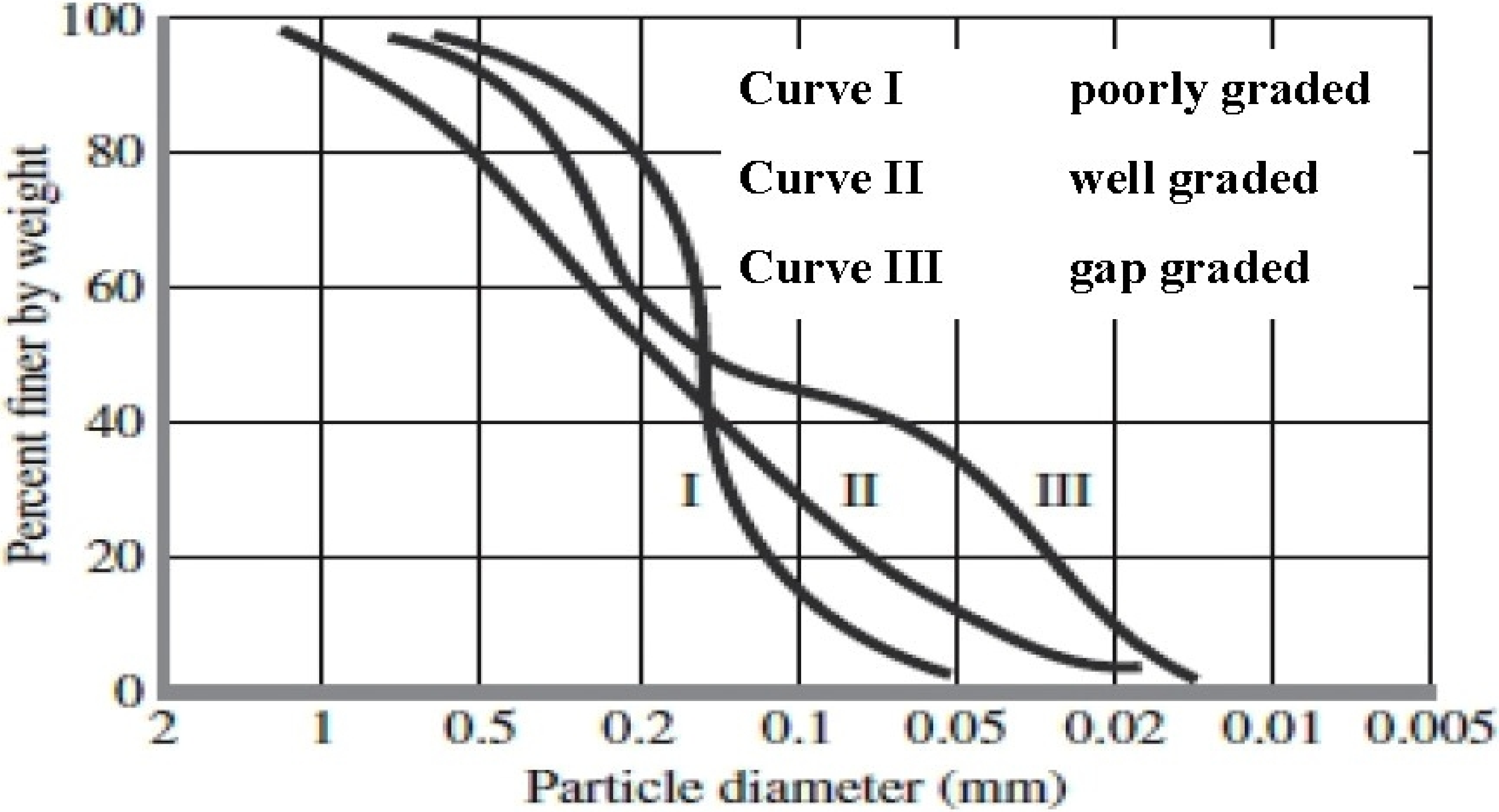
Uniformity Coefficient Cu

$$C_u = \frac{D_{60}}{D_{10}}$$

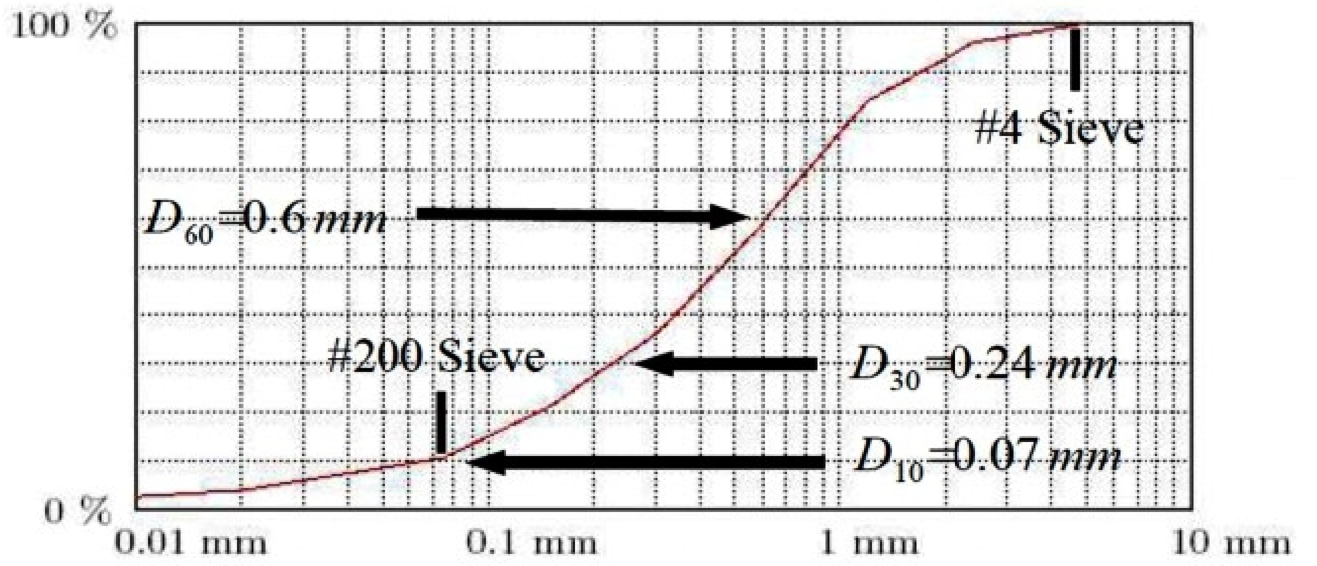
Coefficient of Curvature Cc

$$Cc = \frac{D^2{}_{30}}{D_{10} D_{60}}$$




100
80
60
40
20
0
Percent finer by weight
2
1
0.5
0.2
0.1
0.05
0.02
0.01
0.005
Particle diameter (mm)
I
II
III
Curve I poorly graded
Curve II well graded
Curve III gap graded

Sieve Analysis Example



$$C_u = \frac{D_{60}}{D_{10}} = \frac{0.6}{0.07} = 8.5$$

$$Cc = \frac{D^2{}_{30}}{D_{10}D_{60}} = \frac{0.24^2}{0.07x0.6} = 1.37$$

Weight-Volume Relationships, Plasticity, and Structure of Soil

Topics

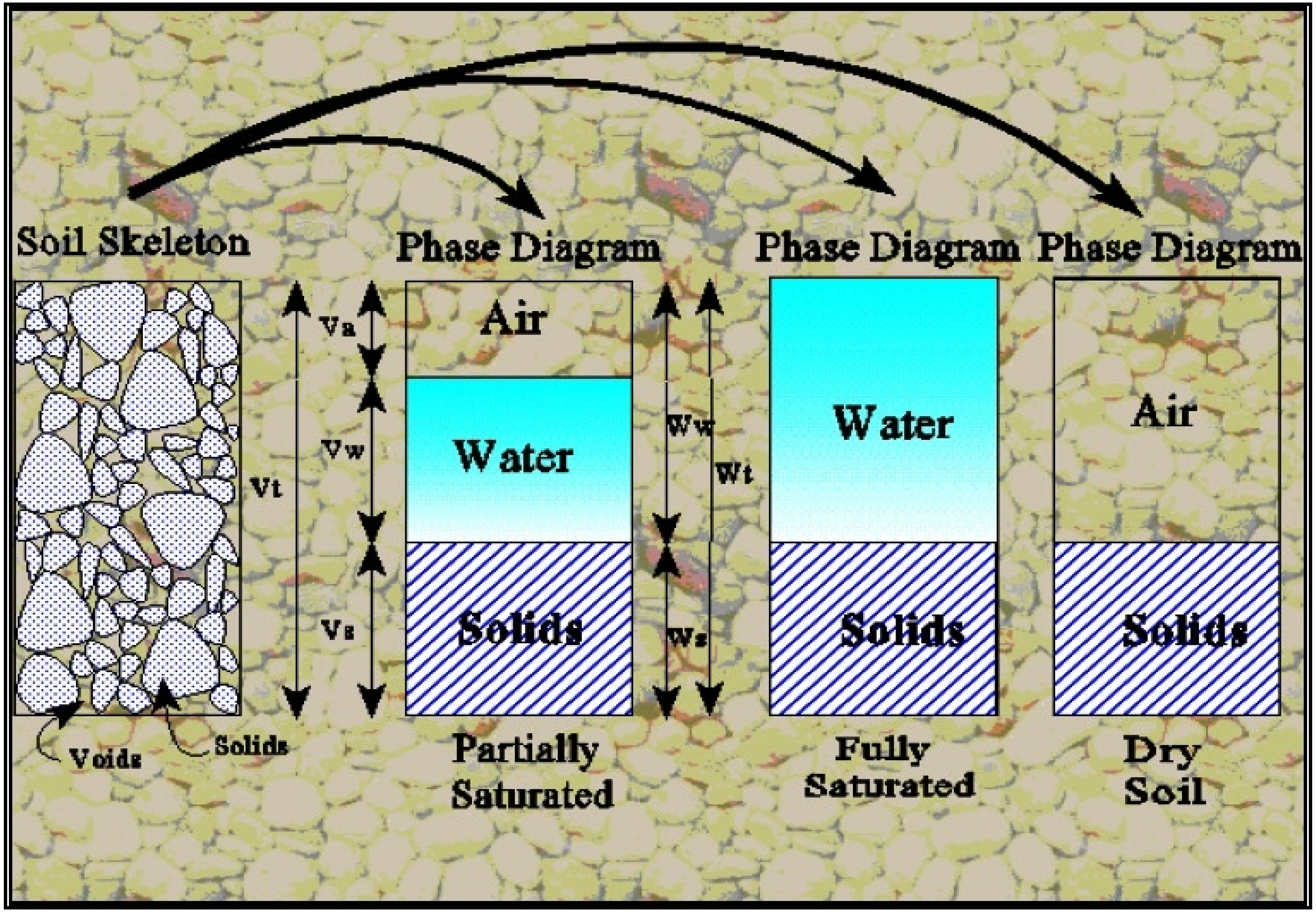
- Basic Concepts
- Phase Diagram
- Important variables-
  (Water or Moisture Content-Unit Weight or Mass-Void ratio-Specific Gravity……..etc.
- Atterberg limits and consistency indices
- Soil Structure and Fabric

Basic Concepts

- Soil is a collection of particles that do not form a totally solid substance
- Soil is a combination of:
  - Soil material in particles
  - Air
  - Water

- The relationship between this combination defines much of what any particular soil can do to support foundations

Phase Diagram



Basic Formulas

$V_{total} = V_{air} + V_{water} + V_{soil}$

$W_{total} = W_{water} + W_{soil}$ **or** $M_{total} = M_{water} + M_{soil}$

$W_x = \gamma_x \times V_x$ **or** $M_x = \rho_x \times V_x$

Specific Gravity and Density

● Unit Weight of Water (γ_w) ◆ 62.4 lb/ft^3 ◆ 9.81 kN/m^3≈10 kN/m^3	Density of Water ◆ 1.95 slugs/ft^3 ◆ 1 g/cm^3 = 1 Mg/m^3 = 1 Metric Ton/m^3

Typical Specific Gravities for Soil Solids

◆ Quartz Sand: 2.64 – 2.66 ◆ Silt: 2.67 – 2.73 ◆ Clay: 2.70 – 2.9	◆ Chalk: 2.60 – 2.75 ◆ Loess: 2.65 – 2.73 ◆ Peat: 1.30 – 1.9 ◆ Except for organic soils, range is fairly narrow

Weight and Volume Relationships

$$W_x = G_x \times \gamma_w \times V_x$$

$$M_x = G_x \times \gamma_w \times V_x$$

In most cases, calculations in soil mechanics are done on a weight basis. Exceptions include wave propagation problems (earthquakes, pile dynamics,……. etc.)

Important Variables

1. ***Void ratio, e***

$$e = \frac{Vv}{Vs}$$ Expressed as decimal Sands (0.4 – 1.0) Clays (0.3 – 1.5)

2. ***Porosity , n***

$$n = \frac{Vv}{Vt} x100\%$$ Expressed as percentage (0-100%)

Prove that $n = \frac{e}{1+e}$ or $e = \frac{n}{1-n}$

3. Degree of saturation, S

$$S = \frac{Vw}{Vv} x100\%$$

S = 0 % Dry Soil, S = 100 % Saturated soil

4. Air Content, Ac

$$Ac = \frac{Va}{V} x100\%$$

So we can show that $Ac = n(1-S)$

5. Water Content, ω

$$\omega = \frac{Ww}{Ws} x100\%$$

ω can be equal to zero in dry soil and may be reached 500% in some marine and organic soils.

6. *Unit weight, γ*

Total unit weight, $\gamma_t = \dfrac{Wt}{Vt} = \dfrac{Ws + Ww}{Vt}$

Solid unit weight, $\gamma_s = \dfrac{Ws}{Vs}$ γ_s range (25.4 kN/m^3 - 28.5 kN/m^3)

Water unit weight, $\gamma_w = \dfrac{Ww}{Vw}$

There are three other useful densities in soils engineering; they are

- Dry Unit weight, $\gamma_d = \dfrac{Ws}{Vt}$
- Saturated Unit Weight, $\gamma_{sat} = \dfrac{Ws + Ww}{Vt} = \dfrac{W_t}{V_t}$ (Va = 0, S = 100 %)
- Submerged Unit Weight, $\gamma^{/} = \gamma_{sat} - \gamma_w$

7. Specific gravity

$$G = \frac{\gamma}{\gamma_w} \quad \text{apparent} \qquad\qquad G_s = \frac{\gamma_s}{\gamma_w} \quad \text{Solid}$$

From the basic definitions provided above, other useful relationships can be derived such as:

$$\gamma_t = \frac{1+\omega}{1+e} G_s \gamma_w = \frac{G_s + Se}{1+e} \gamma_w \qquad \gamma_d = \frac{\gamma_t}{1+\omega} = \frac{G_s}{1+e} \gamma_w \qquad \gamma_{sat} = \frac{G_s + e}{1+e} \gamma_w$$

$$\gamma' = \frac{G_s - 1}{1+e} \gamma_w$$

$$Se = G_s \omega$$

H.W #1 prove these equations using basic definitions

Solutions of phase problems

Probably the single most important thing you can do in solving phase problems is to draw a phase diagram & remember the following simple rules,

1. Remember the basic definitions of ω, e, γs , S, ………etc.
2. Assume either Vs = 1 or Vt = 1 if not given
3. Often use $Se = G_s\omega$

Various Unit-Weight 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	$\frac{(1+w)G_s\gamma_w}{1+e}$	γ, w	$\frac{\gamma}{1+w}$	G_s, e	$\frac{(G_s+e)\gamma_w}{1+e}$
S, G_s, e	$\frac{(G_s+Se)\gamma_w}{1+e}$	G_s, e	$\frac{G_s\gamma_w}{1+e}$	G_s, n	$[(1-n)G_s+n]\gamma_w$
w, G_s, S	$\frac{(1+w)G_s\gamma_w}{1+\frac{wG_s}{S}}$	G_s, n	$G_s\gamma_w(1-n)$	G_s, w_{sat}	$\left(\frac{1+w_{sat}}{1+w_{sat}G_s}\right)G_s\gamma_w$
w, G_s, n	$G_s\gamma_w(1-n)(1+w)$	G_s, w, S	$\frac{G_s\gamma_w}{1+\left(\frac{wG_s}{S}\right)}$	e, w_{sat}	$\left(\frac{e}{w_{sat}}\right)\left(\frac{1+w_{sat}}{1+e}\right)\gamma_w$
S, G_s, n	$G_s\gamma_w(1-n)+nS\gamma_w$	e, w, S	$\frac{eS\gamma_w}{(1+e)w}$	n, w_{sat}	$n\left(\frac{1+w_{sat}}{w_{sat}}\right)\gamma_w$
		γ_{sat}, e	$\gamma_{sat}-\frac{e\gamma_w}{1+e}$	γ_d, e	$\gamma_d+\left(\frac{e}{1+e}\right)\gamma_w$
		γ_{sat}, n	$\gamma_{sat}-n\gamma_w$	γ_d, n	$\gamma_d+n\gamma_w$
		γ_{sat}, G_s	$\frac{(\gamma_{sat}-\gamma_w)G_s}{(G_s-1)}$	γ_d, S	$\left(1-\frac{1}{G_s}\right)\gamma_d+\gamma_w$
				γ_d, w_{sat}	$\gamma_d(1+w_{sat})$

Example 1

For saturated sample with void ratio e = 0.6 and Gs = 2.65 .

Find:

1. porosity
2. moisture or water content
3. total unit weight

Solution:

Let Vs = 1 m^3 and γ_w = 10 kN/m^3

$$e = \frac{V_v}{V_s} \Rightarrow V_v = eV_s = 0.6x1 = 0.6m^3$$

$$G_s = \frac{\gamma_s}{\gamma_w} = \frac{\frac{W_s}{V_s}}{\gamma_w} \Rightarrow W_s = V_s \gamma_w G_s = 1x10x2.65 = 26.5KN$$

Since the sample is saturated then S=100%

$$\therefore V_w = V_v = 0.6\,\mathrm{m}^3$$

$$\gamma_w = \frac{W_w}{V_w} \Rightarrow W_w = \gamma_w V_w = 10x0.6 = 6KN$$

$$W_t = W_w + W_s = 6 + 26.5 = 32.5KN$$

$$V_t = V_s + V_v = 1 + 0.6 = 1.6m^3$$

$$n = \frac{V_v}{V_t} = \frac{0.6}{1.6}x100\% = 37.5\%$$

$$\omega = \frac{W_w}{W_s} = \frac{6}{26.5}x100\% = 27.7\%$$

$$\gamma_t = \frac{W_t}{V_t} = \frac{32.5}{1.6} \approx 20KN/M^3$$

Example 2

A soil sample with dry unit weight γ_d = 18.5 KN/m^3 & specific gravity of solids Gs = 2.68 submerges with water, the void ratio increases by 20%. Find-

1. The porosity of the soil before it was merged
2. The weight of 2 m3 of the soil under the water table.

Solution:

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

$$18.5 = \frac{2.68}{1+e} x10 \Rightarrow e = 0.449 = e_{dry}$$

$$\therefore n = \frac{e}{1+e} = \frac{0.449}{1+0.449} x100\% \cong 31\%$$

Since void ratio increased by 20% after it had been submerged

$$\therefore e_{sat} = 1.2 e_{dry} = 0.539$$

$$\gamma' = \frac{G_s - 1}{1 + e}\gamma_w = \frac{2.68 - 1}{1 + 0.539} x10 = 10.92 \quad kN / m^3$$

The weight of 2 m^3 of submerged soil,

$$W_{sub} = \gamma'.2 = 21.84 \quad kN$$

Example 3

A sample of saturated soil with ω = 14 % and Gs = 2.7.

Find void ratio, total unit weight, and dry unit weight

Solution

$$Se = G_s\omega \Rightarrow (1)e = (2.7)(0.14) \Rightarrow e = 0.38$$

$$\gamma_t = \frac{1+\omega}{1+e} G_s \gamma_w = \frac{1+0.14}{1+0.38} x2.7x10 = 22.3 \quad kN/m^3$$

$$\gamma_d \frac{\gamma_t}{1+\omega} = \frac{22.3}{1+0.14} = 19.56 \quad kN/m^3$$

or

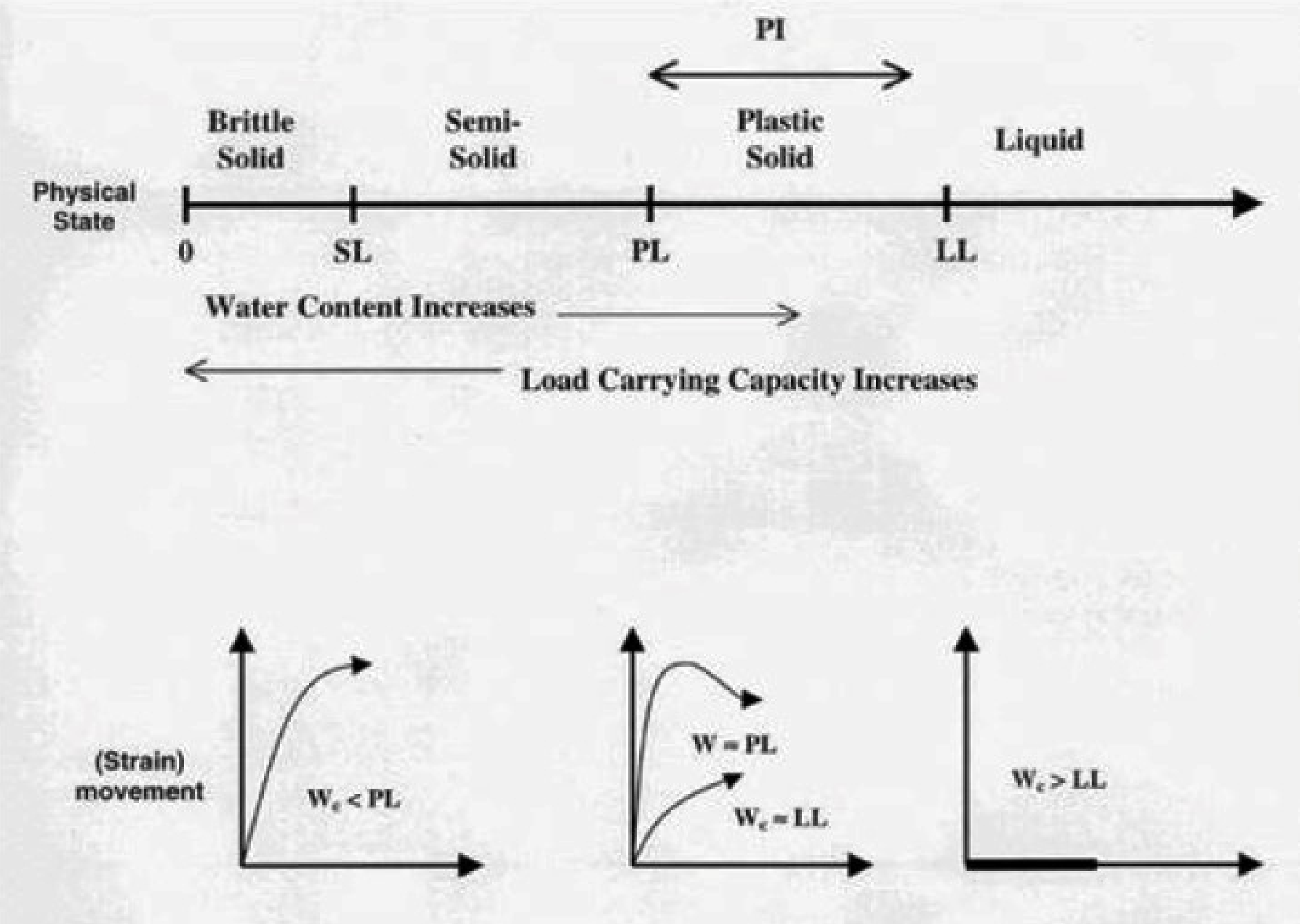
$$\gamma_d \frac{G_s}{1+e}\gamma_w = \frac{2.7}{1+0.38} = 19.56 \quad kN/m^3$$

Atterberg limits and Consistency indices

They are water contents at certain limiting or critical stages in soil behavior (especially, fine- grained soils). They, along with the natural water content (ω_n) are the most important items in the description of fine- grained soils and they are correlated with the engineering properties & behavior of fine- grained soils.

They are-

1- Liquid Limit (L.L or ω_L).
2- Plastic Limit (P.L or ω_P).
3- Shrinkage limit (S.L or ω_S).

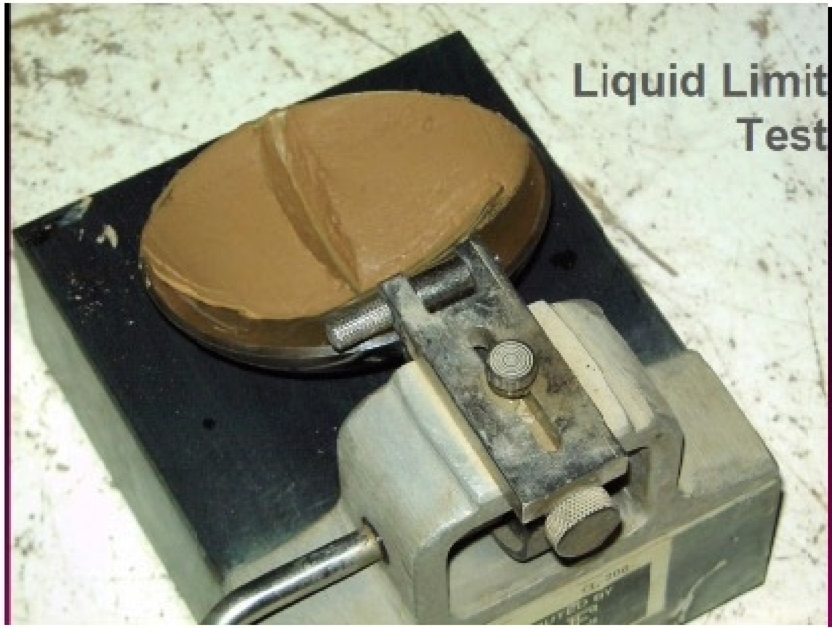


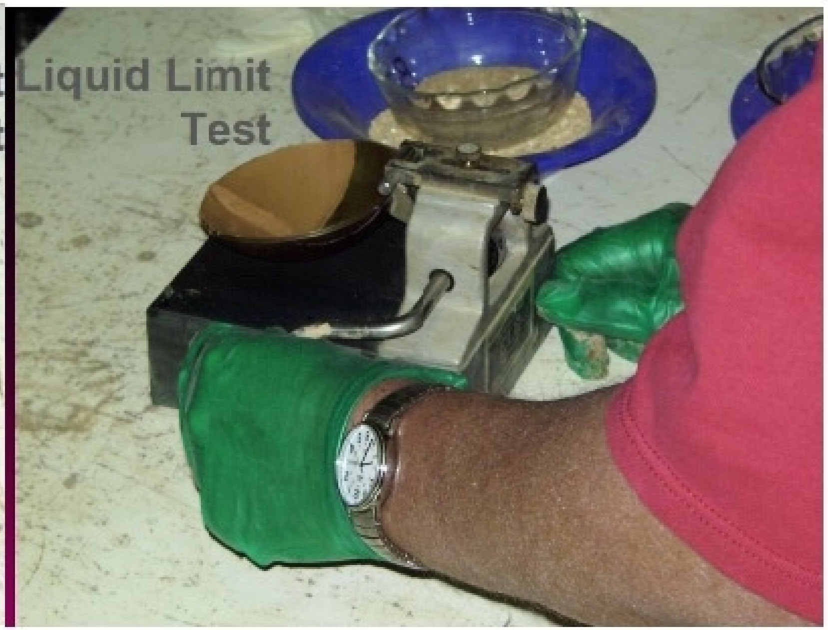
(From Holts & Kovacs)

Liquid Limit

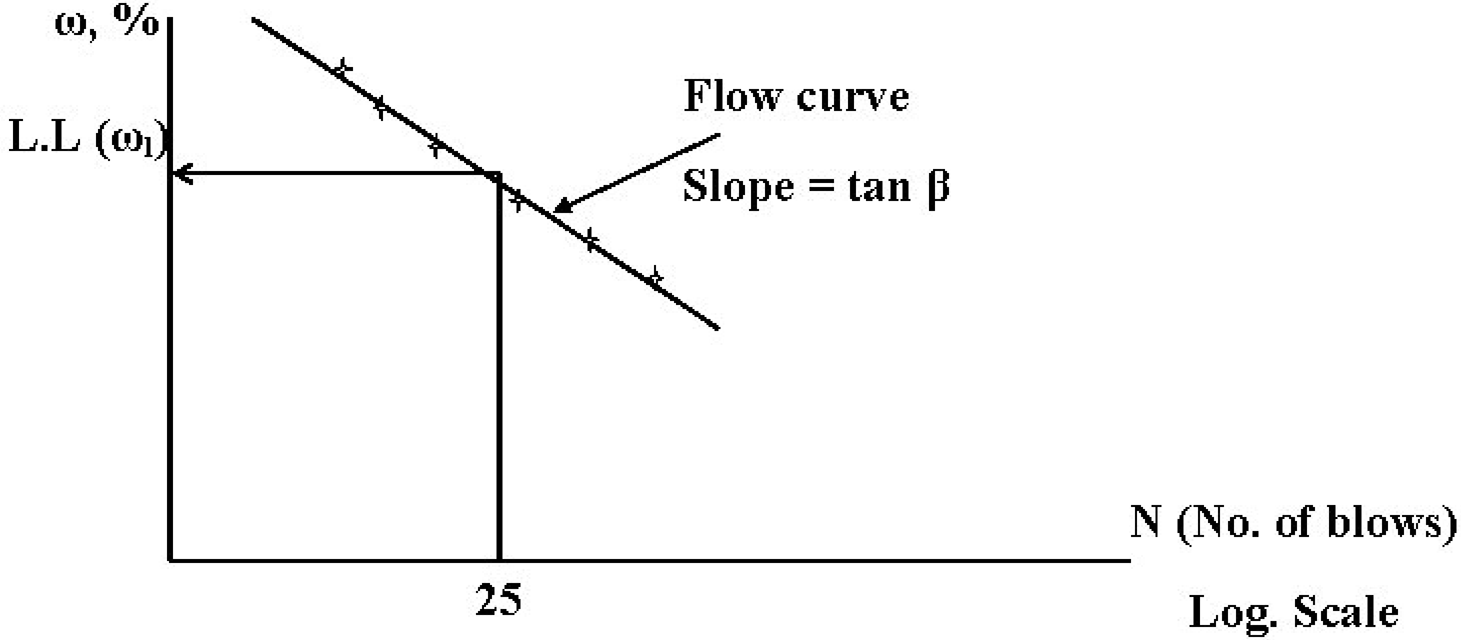
Definition

Atterberg defined the liquid limit as a water content at which the soil becomes a viscous liquid.



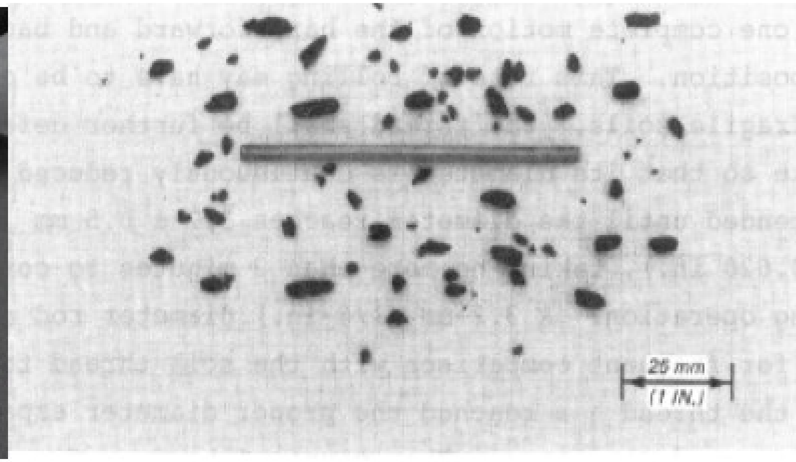


In practice, it is difficult to mix the soil so that the groove closure occurs at exactly 25 blows, so Casagrande did the following:



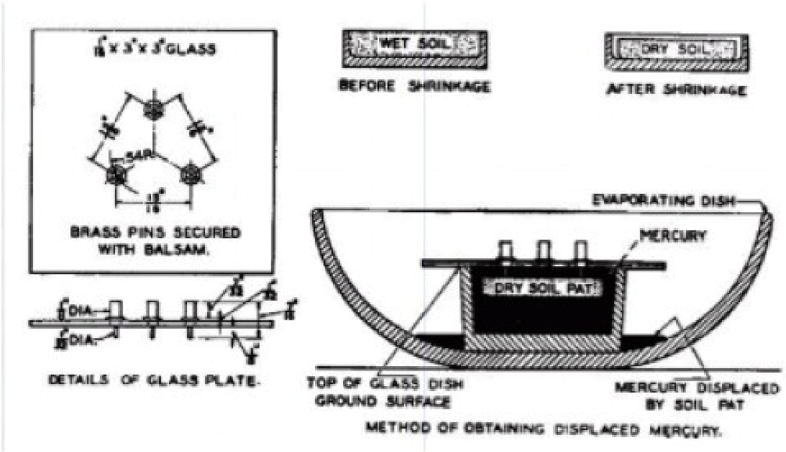
Plastic Limit

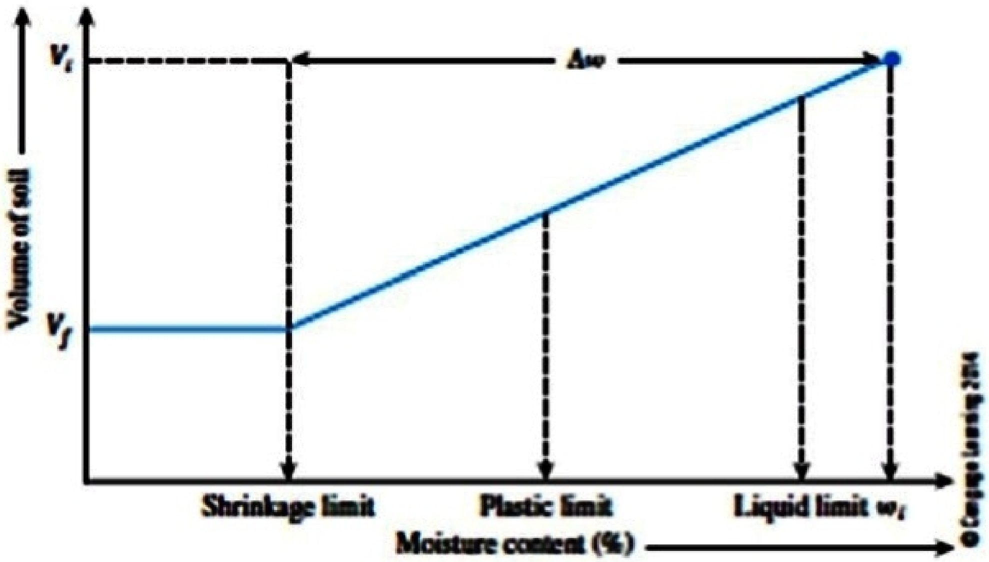
Atterberg defined the plastic limit as water content at which soil becomes in a plastic state.



Shrinkage Limit

It defines as a water content at which no further volume change occurs with continuous loss of moisture.





Other index properties for the soil

- Plasticity index, $P.I = L.L - P.L$

- Flow index, $$F.I = \frac{\omega_2 - \omega_1}{\log N_2 - \log N_1} = \frac{\Delta\omega}{\log \frac{N_2}{N_1} = 1 \; for \ldots one \ldots cycle} = \Delta\omega$$

the slope of flow curve, it shows how close the clayey soil from the plastic state

- Toughness index,

$$T.I = \frac{P.I}{F.I}$$ express the soil consistency in the plastic State.

- Consistency index,

$$C.I = \frac{L.L - \omega_n}{L.L - P.L} = \frac{L.L - \omega_n}{P.I}$$

- Liquidity index,

- $$L.I = \frac{\omega_n - P.L}{P.I}$$

L.I < 0 --- the soil is in Brittle state

L.I (0 –1) – the soil is in plastic state

L.I >1 --- the soil is in viscous liquid state

Factors affecting the Atterberg Limits

1. Shape and size of grains.

As the grains size gets smaller the plasticity increases while grains with flaky shape had more plasticity characteristics than other shapes.

2. The content of clay minerals.

As the content of clay minerals increase the plasticity characteristics increase.

3. Type of clay minerals.

As we will describe later the characteristics of each type of clay mineral group the type will affect the plasticity characteristics and for instance

Montomorillonite ↑ **Plasticity increase**

Illite

4. Type of ions.

The type of absorbed ions will affect the plasticity characteristics such as Na; Mg will give high plasticity while Ca will give low plasticity.

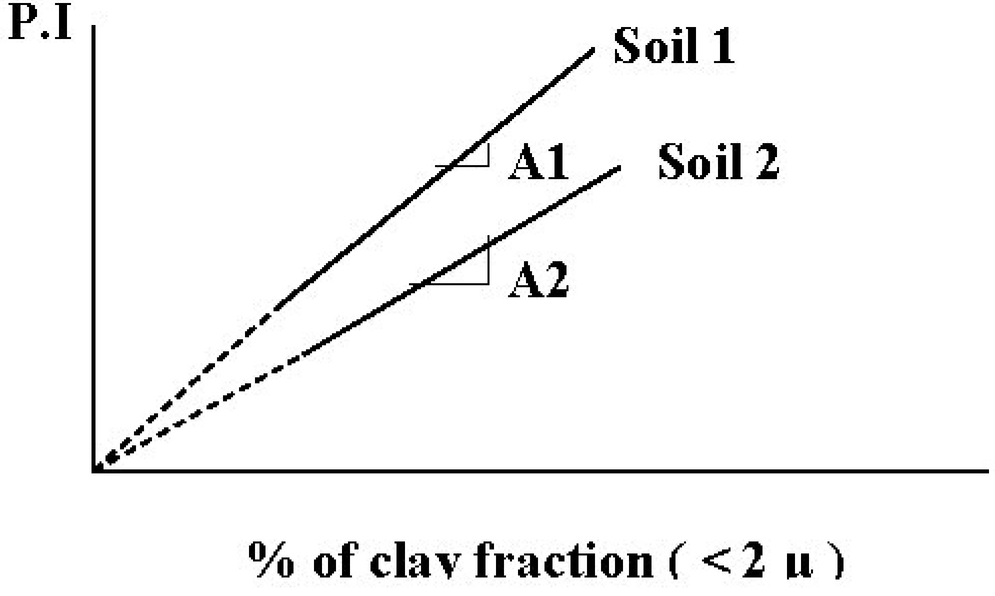
5. The content of organic matter.

As the organic matter content increase the plasticity characteristics Increase.

Activity

Skempton (1953) observed the following relationship. He defined a quantity called "*Activity*" which the slope of the line correlating P.I & % finer than 2 μm.

$$A = \frac{P.I}{\% of clay - size fraction, by weight}$$



This term used for identifying the swelling potential of clay soils and for certain classification properties.

A	Soil classification
< 0.75	Non Active
0.75 – 1.25	Normally Active
1.25 – 2.0	Active

A	Type of clay minerals
0.4 – 0.5	Kaolinite
0.5 – 1.0	Illite
1.0 – 7.0	Montomorillonite

Example

The following data were obtained from the liquid & plastic limits tests for a soil with ω_n = 15 %

Liquid limit test		**Plastic limit test**
No. of blows	**Moisture content;ω %**	**P.L = 18.7 %**
15	**42**	
20	**40.8**	
28	**39.1**	

Required

a- Draw the flow curve & find the liquid limit.

b- Find the plasticity index of the soil

c- Find L.I, C.I, F.I, T.I

Solution

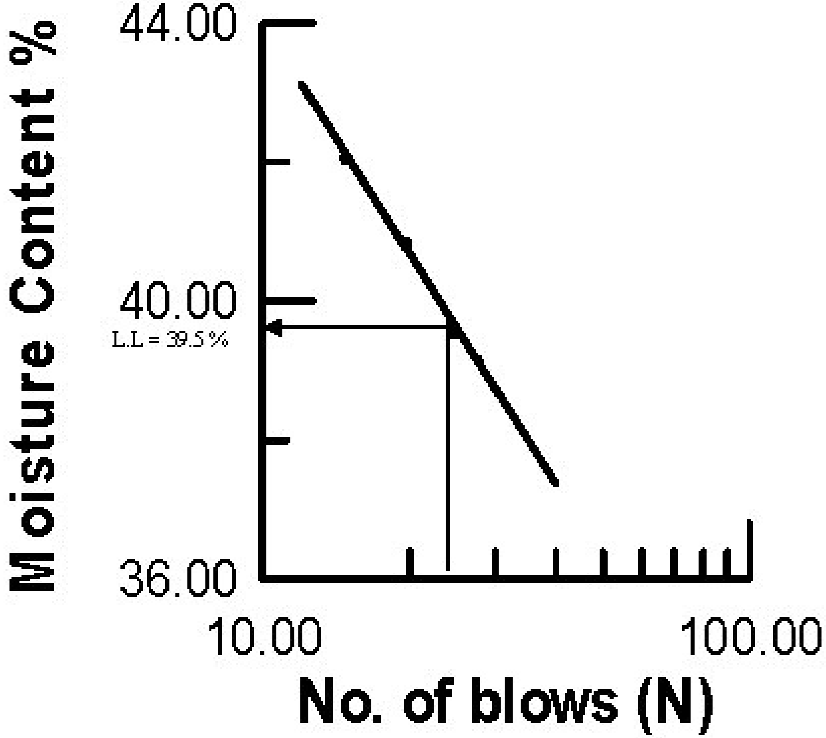
$$P.I = L.L - P.L = 39.5 - 18.7 = 20.8$$

$$L.I = \frac{\omega_n - P.L}{P.I} = \frac{15 - 18.7}{20.8} = -0.178 < 1$$

$$C.I = \frac{L.L - \omega_n}{P.I} = \frac{39.5 - 15}{20.8} = 1.178$$

$$F.I = \frac{42 - 40.8}{\log 15 - \log 20} = -9.6$$

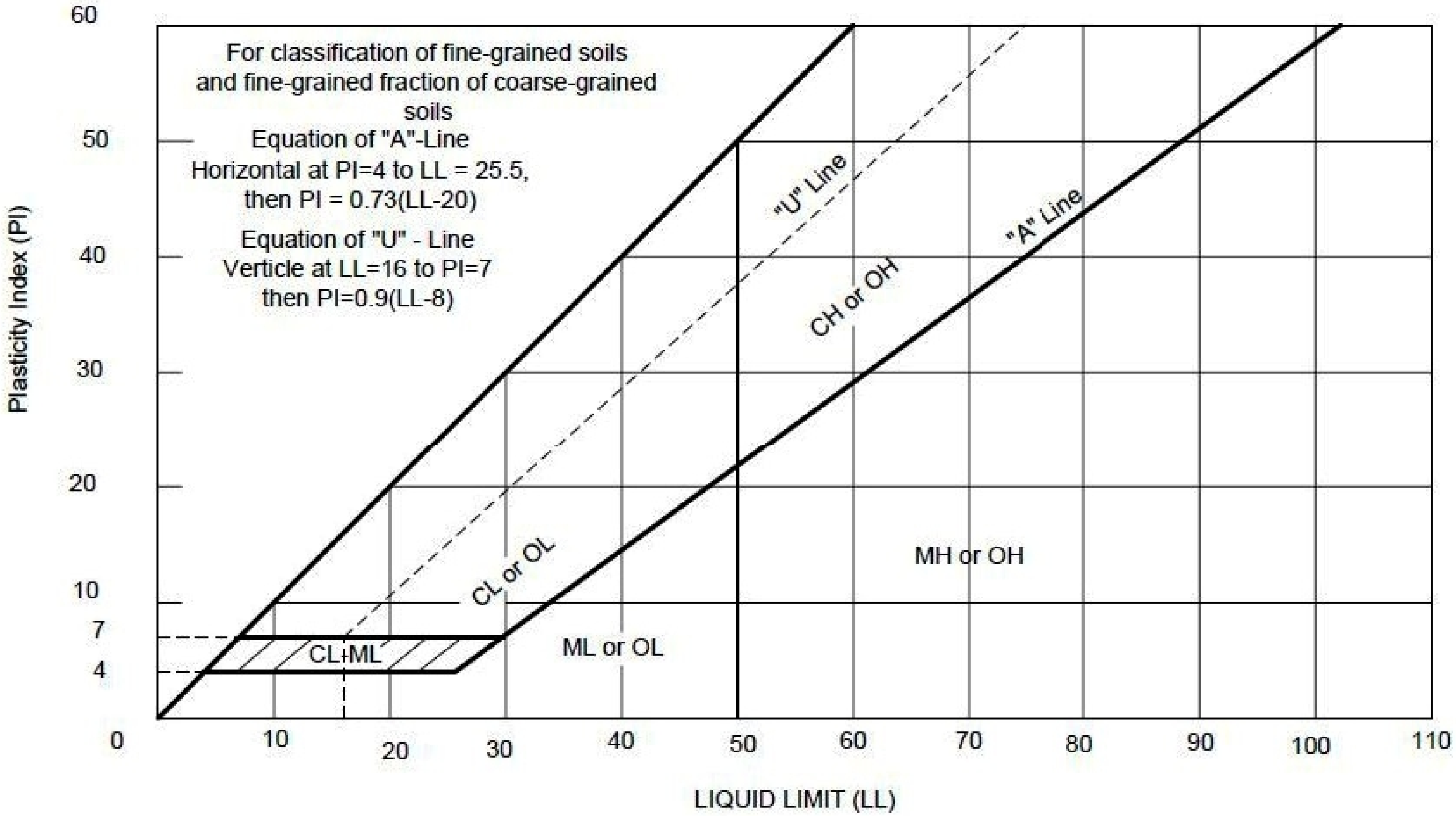
$$T.I = \frac{P.I}{F.I} = \frac{20.8}{9.6} = 2.167$$

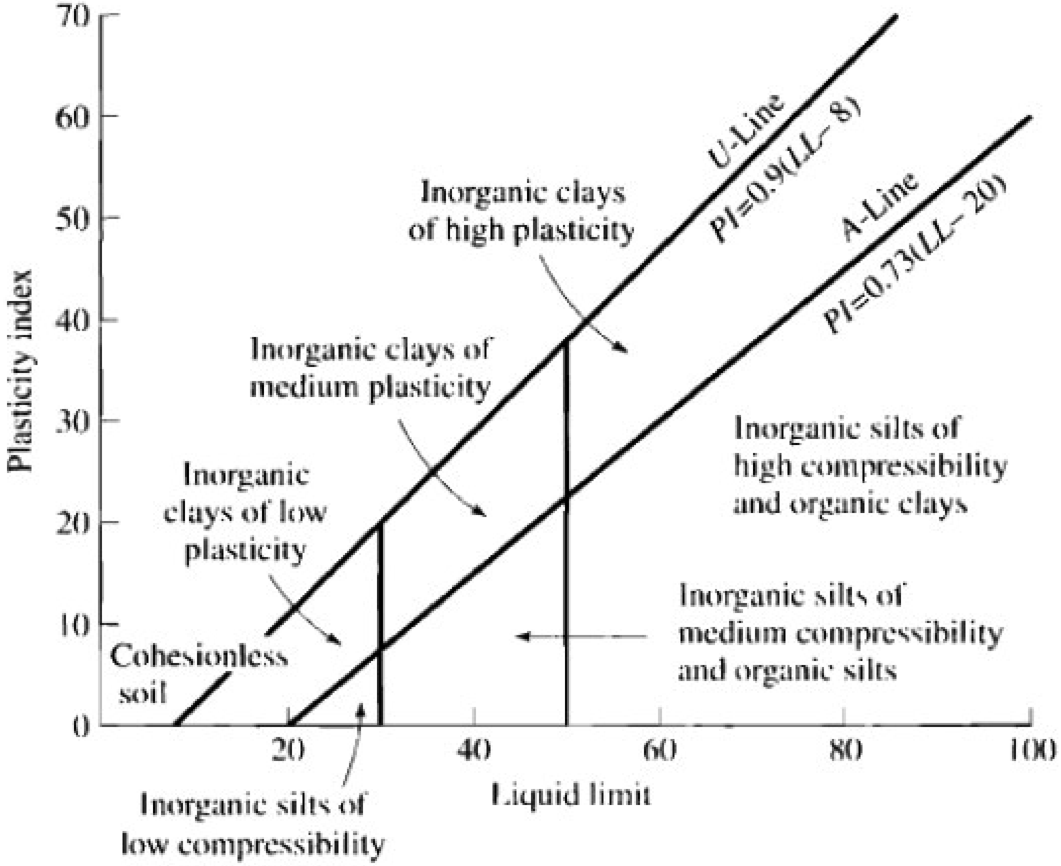


The soil is heavily preconsolidated since ω_n is smaller than P.L & lower than L.L.

Plasticity Chart

Casagrande (1932)




70
60
50
40
30
20
10
0
Plasticity index
U-Line
PI=0.9(LL−8)
A-Line
PI=0.73(LL−20)
Inorganic clays
of high plasticity
Inorganic clays of
medium plasticity
Inorganic
clays of low
plasticity
Cohesionless
soil
Inorganic silts of
high compressibility
and organic clays
Inorganic silts of
medium compressibility
and organic silts
20
40
60
80
100
Liquid limit
Inorganic silts of
low compressibility

Soil Structure and Fabric

In geotechnical engineering, the structure of a soil affects or governs the engineering behavior of particular soil and is taken to mean both –

1. ***Geometric arrangement*** of the particles or mineral grains with respect to each other (soil fabric).
2. ***Interparticle forces*** *which may act between the particles or minerals grains. They probably have two main causes : Orientation of the adsorbed water and Cementation*

Factors that affect the soil structure are-

- The shape, size, and mineralogical composition of soil particles,
- The nature and composition of soil water.

Structures in Cohesionless Soil

The structures generally encountered in cohesionless soils can be divided into two major categories:-

1. *Single – grained structure*
2. *Honeycombed structure*

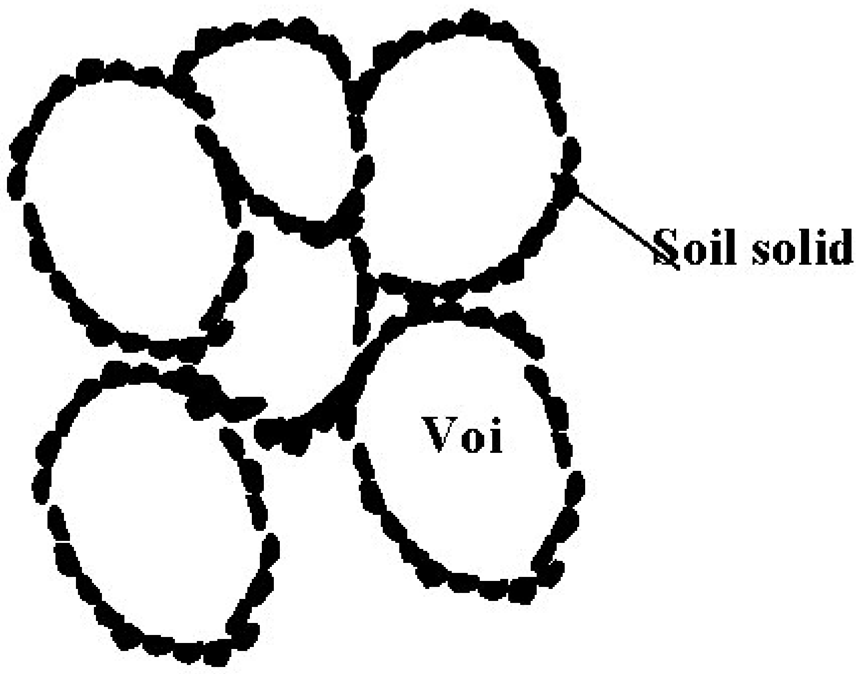
Single – grained structure

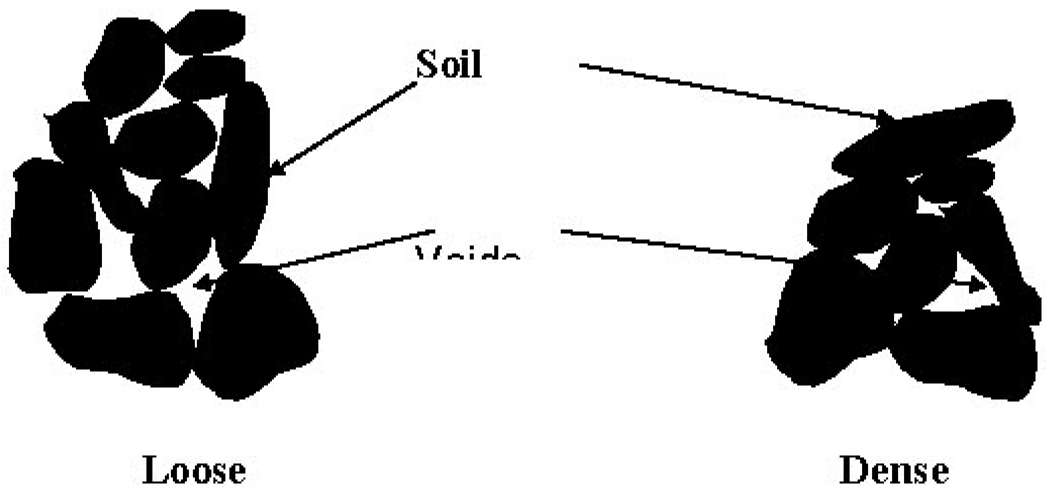
A useful way to characterize the density of a natural granular soil is with relative density D_r as described before.

Honeycombed structure

In this structure, relatively fine sand and silt form small arches with chains of particles as shown in the figure below. Soils exhibiting honeycombed structure have large void ratios and they can carry the ordinary static load.

However, under heavy load or when subjected to shock loading, the structure breaks down, resulting in large settlement.





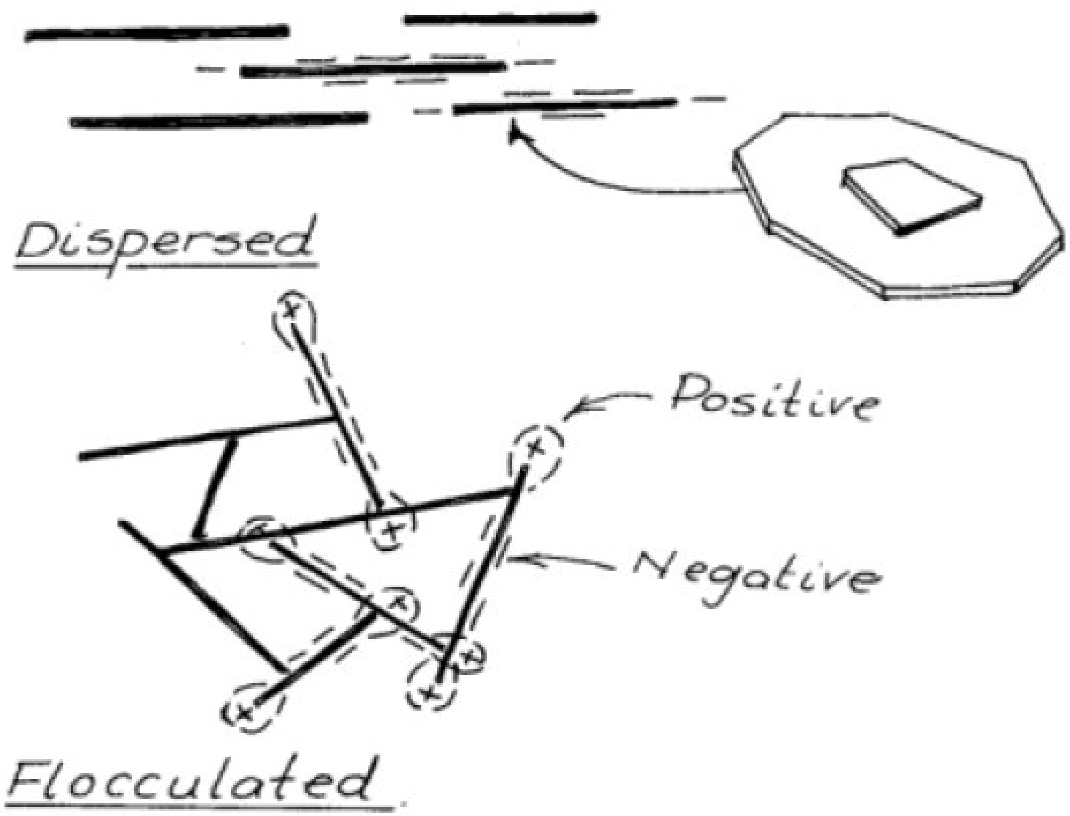
Structures in Cohesive Soils

1. *Dispersed structure*
2. *Flocculated structure*

The interparticle forces are relatively large, so that the interparticle forces and the geometric arrangement of the grains will make the structure in cohesive soils.

If two particles approach each other in a suspension, the forces acting on them are

1. the Van der Waals forces of attraction, and
2. the repulsion between the two positively ionised adsorbed layers.



Soil Classification

Introduction

A soil classification system-

- It is the arrangement of different soils with similar properties into groups & subgroups based on their application or to their probable engineering behavior.
- It provides a common language to briefly express the general characteristics of soils, which are infinitely varied, without detailed descriptions.
- Most of the soils classification systems that have been developed for engineering purposes are based on simple index properties such as ***particle size distribution & plasticity.***
- Although there are several classification systems now in use, none is totally definitive of any soil for all possible applications, because of the wide diversity of soil properties.

The role of classification system in geotechnical engineering practice is-

Classification & index properties

e, n, γ, S, GDS, L.L, P.I, ……etc

↓

Classification system

↓

Engineering properties

Permeability, compressibility, Shear strength,….etc.

↓

Engineering purposes

Highways, airfield, dams, foundations,…etc.

A- Textural classification

In general classification systems divided soils into the following categories on the basis of particle size. *Gravel; Sand; Silt; and Clay,*

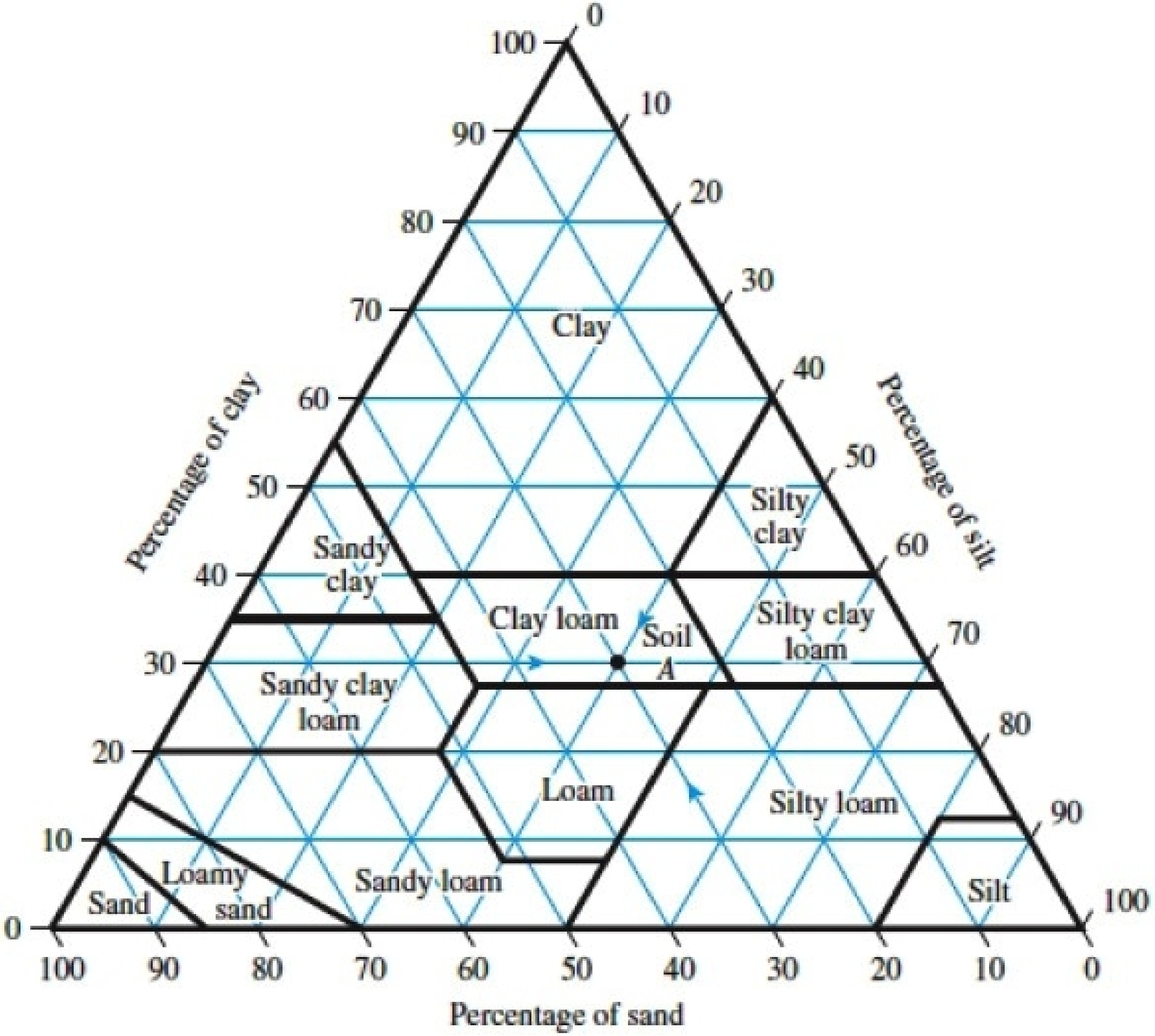
but the nature of soils are mixtures of particles from several size groups, so if we know the principle components of the soils, we can name the soils such as Sandy Clay, Silty Clay ; and so forth.

One of these systems is the system developed by AASHTO (American Association of State Highway and Transportation Official).the the following chart is used to classify the soil, It is based on the particle size limits

Sand – size 2.0 – 0.05 mm in diameter

Silt – size 0.05 – 0.002 mm in diameter

Clay – size smaller than 0.002 mm in diameter


Percentage of clay
Percentage of silt
Percentage of sand
Clay
Silty clay
Sandy clay
Clay loam
Soil A
Silty clay loam
Sandy clay loam
Loam
Silty loam
Sandy loam
Loamy sand
Sand
Silt
0 10 20 30 40 50 60 70 80 90 100
100 90 80 70 60 50 40 30 20 10 0

The chart is based only on the fraction of the soil that passes through the no. 10 sieve. Otherwise, a correction will be necessary if a certain percentage of the soil particles are larger than 2 mm in diameter, as shown below-

The modified textural composition are-

$$\text{Modified \% Sand} = \frac{\%\boldsymbol{sand}}{100 - \%\boldsymbol{gravel}} \boldsymbol{x}100\%$$

$$\text{Modified \% Silt} = \frac{\%\boldsymbol{silt}}{100 - \%\boldsymbol{gravel}} \boldsymbol{x}100\%$$

$$\text{Modified \% Clay} = \frac{\%\boldsymbol{clay}}{100 - \%\boldsymbol{gravel}} \boldsymbol{x}100\%$$

Then the soil is classified by proceeding in the manner indicated by the arrows & the soil named according to the zone that falls in it as shown in the following example.

Example

Given

	Particle – size distribution (%)			
Soil	*Gravel*	*Sand*	*Silt*	*Clay*
A	0	18	24	58
B	18	~~51~~ 62.2	~~22~~ 26.83	~~9~~ 10.96

Required-

Classify the soils using textural classification of AASHTO

Solution- Soil B percentages need to be corrected while percentages of soil A need no correction and we can use the % directly

Soil B

$$\text{Modified \% Sand} = \frac{51}{100-18}x100 = 62.2\%$$

$$\text{Modified \% Silt} = \frac{22}{100-18} = 26.83\%$$

$$\text{Modified \% Clay} = \frac{9}{100-18} = 10.96\%$$

Using AASHTO chart we classified the soil A as clay and soil B As gravelly Sandy loam

Other classification systems

1-AASHTO System

2-Unified Soil Classification System (USCS).At present, we will consider (USCS) only

			SAND					
AASHTO	**BOULDERS**	**GRAVEL**	**COARSE**	**MEDIUM**	**FINE**	**SILT**	**CLAY**	**COLLOIDAL**
	75	4.75	2	0.425	0.075	0.005	0.001	

			GRAVEL		SAND			
USCS	**BOULDERS**	**COBBLES**	**COARSE**	**FINE**	**COARSE**	**MEDIUM**	**FINE**	**FINES (SILT & CLAY)**
	300	75	19	4.75	2	0.425	0.075	

Unified Soil Classification System (USCS)

Casagrande in 1942 during World War 2, it was revised in 1952. At present, it widely used among engineers.

This system classifies soils under two broad categories

1- **Coarse – grained soils** that are gravelly and sandy in nature with less than 50% passing through the no.200 sieve. The group symbols start with prefixes of either **G** or **S**. besides cobble and boulder without the symbol.(see the table in your notes)

2- **Fine – grained soils** with 50% or more passing through the no. 200 sieve. The group symbols start with prefixes **M**; **C**; **O** & **Pt**. (see the tables in your notes).

Other symbols used for the classification are –

W – well graded

P – poorly graded

L – low plasticity (L.L < 50%)

H – high plasticity (L.L > 50%)

So the group symbols may be one of the followings for-

- *Coarse – grained soils*

GW , SW   GW – GM , SW – SM   GM , SM

GP , SP   GW – GC , SW – SC   GC , SC

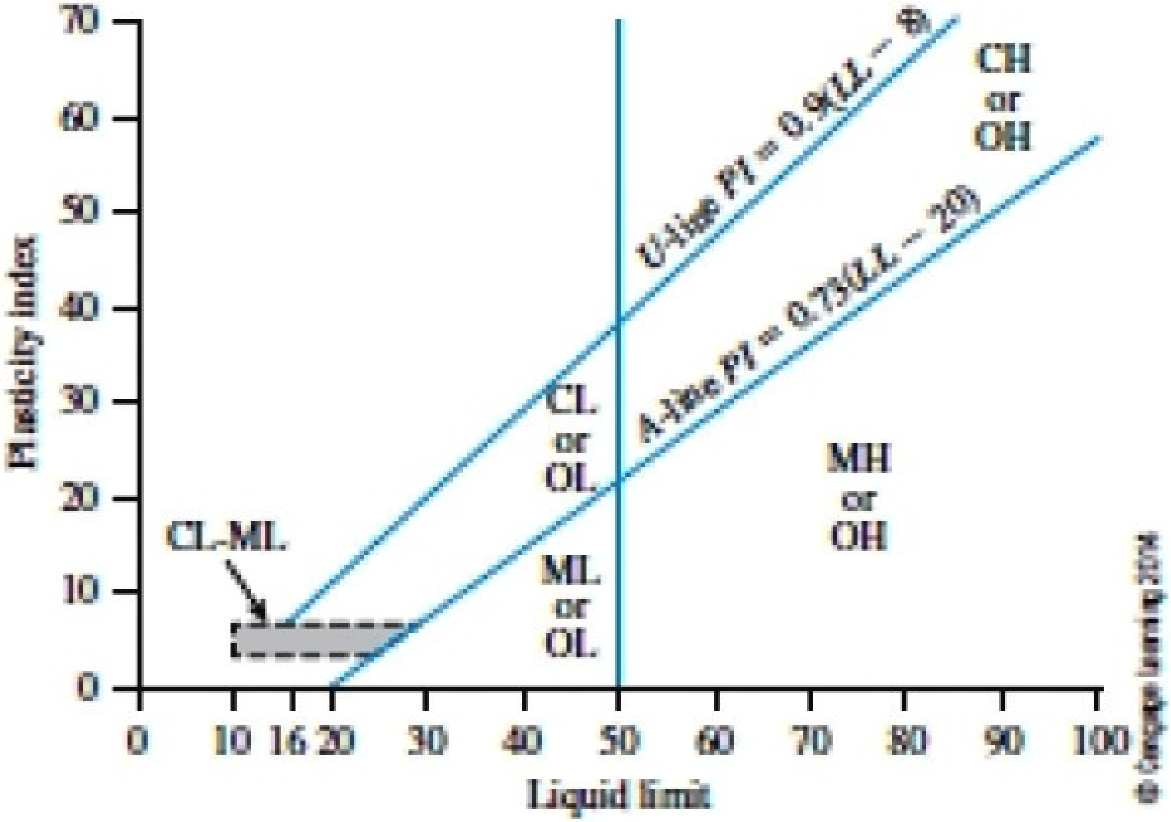
GP – GM , SP – SM

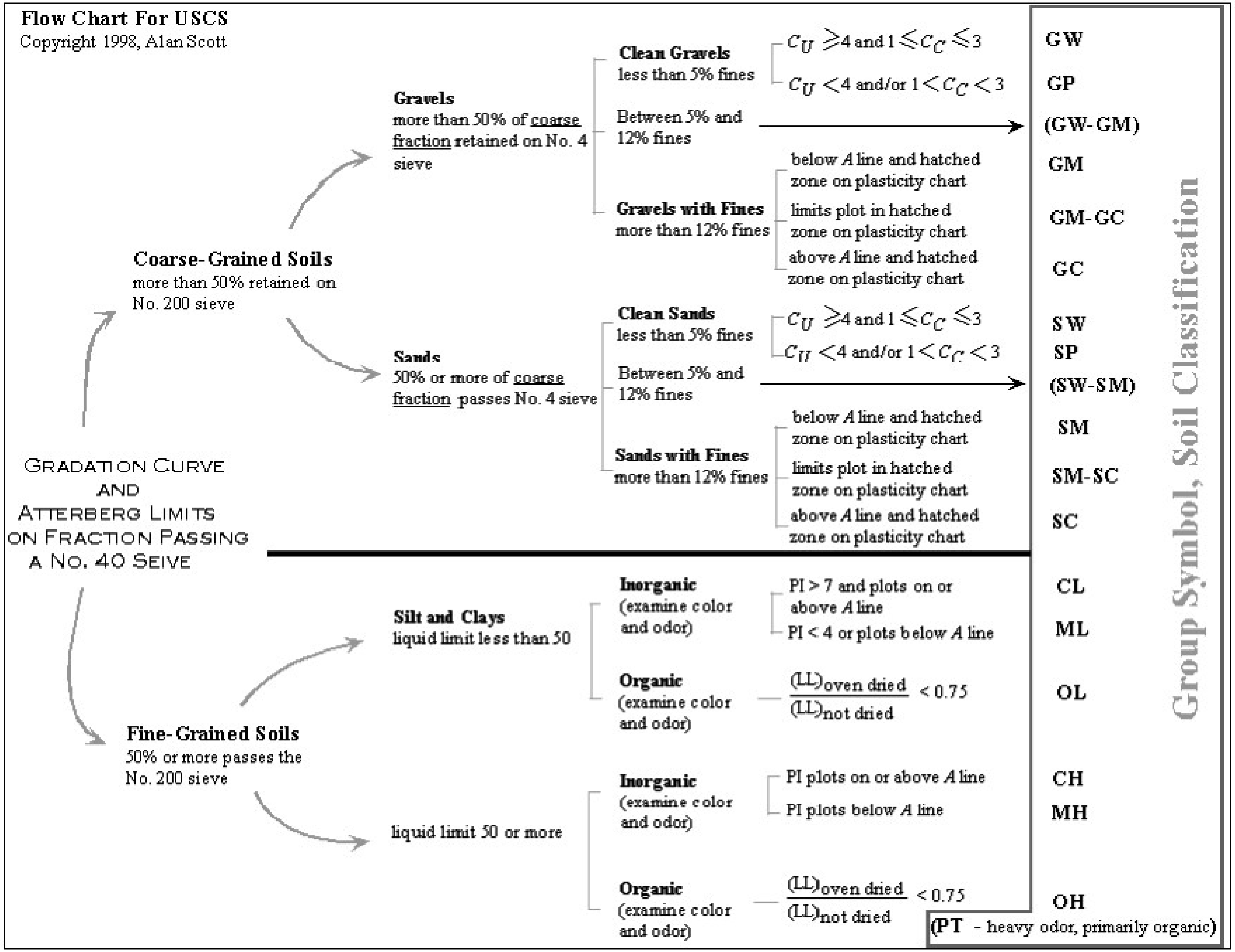
GP – GC , SP – SC

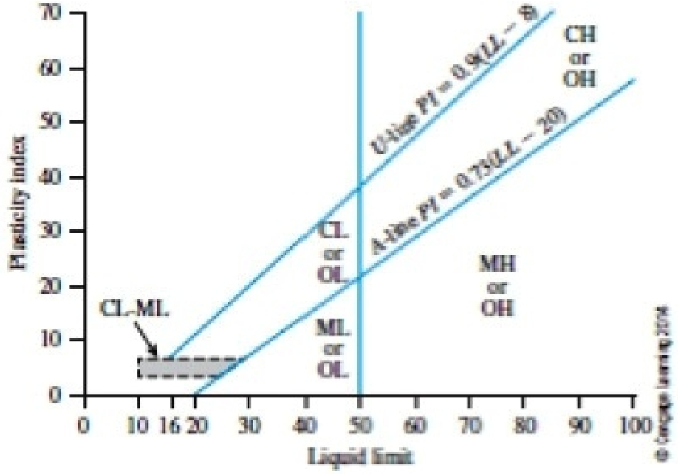
- *Fine – grained soils*

CL , ML , OL   CH , MH , OH   CL – ML &Pt

The plasticity chart used in USCS is shown below which is developed by Casagrande (1948) and modified to some extent here.




Flow Chart For USCS
Copyright 1998, Alan Scott
Gradation Curve and Atterberg Limits on Fraction Passing a No. 40 Seive
Coarse-Grained Soils
more than 50% retained on No. 200 sieve
Gravels
more than 50% of coarse fraction retained on No. 4 sieve
Clean Gravels
less than 5% fines
$C_U \geq 4$ and $1 \leq C_C \leq 3$
$C_U < 4$ and/or $1 < C_C < 3$
Between 5% and 12% fines
Gravels with Fines
more than 12% fines
below A line and hatched zone on plasticity chart
limits plot in hatched zone on plasticity chart
above A line and hatched zone on plasticity chart
Sands
50% or more of coarse fraction passes No. 4 sieve
Clean Sands
less than 5% fines
$C_U \geq 4$ and $1 \leq C_C \leq 3$
$C_U < 4$ and/or $1 < C_C < 3$
Between 5% and 12% fines
Sands with Fines
more than 12% fines
below A line and hatched zone on plasticity chart
limits plot in hatched zone on plasticity chart
above A line and hatched zone on plasticity chart
Fine-Grained Soils
50% or more passes the No. 200 sieve
Silt and Clays
liquid limit less than 50
Inorganic
(examine color and odor)
PI > 7 and plots on or above A line
PI < 4 or plots below A line
Organic
(examine color and odor)
$\frac{(LL)_{oven\ dried}}{(LL)_{not\ dried}} < 0.75$
liquid limit 50 or more
Inorganic
(examine color and odor)
PI plots on or above A line
PI plots below A line
Organic
(examine color and odor)
$\frac{(LL)_{oven\ dried}}{(LL)_{not\ dried}} < 0.75$
Group Symbol, Soil Classification
GW
GP
(GW-GM)
GM
GM-GC
GC
SW
SP
(SW-SM)
SM
SM-SC
SC
CL
ML
OL
CH
MH
OH
(PT - heavy odor, primarily organic)


Plasticity index
Liquid limit
0
10
16
20
30
40
50
60
70
80
90
100
U-line PI = 0.9(LL – 8)
A-line PI = 0.73(LL – 20)
CH or OH
CL or OL
MH or OH
ML or OL
CL-ML

Example

Following are the results of a sieve analysis and L.L & P.L tests for two soils

Sieve size	Soil 1 % passing	Soil 2 % passing
No.4 (4.75 mm)	99	97
No. 10 (2 mm)	92	90
No. 40 (0.475 mm)	86	40
No. 100	78	8
No. 200 (0.075 mm)	60	5
L.L	20	-
P.L	15	-
P.I	5	NP (Not Plastic)

Required

Classify the soil according to USCS

Solution

1-Plot the GSD curve for the two soils.

2-For soil, 1 % passing no. 200 sieve is greater than 50% so it is fine grained soil and by using plasticity chart the soil plots in the zone (CL – ML).

3-For soil 2 % passing no. 200 sieve is less than 50% so it is coarse – grained soil.

F_1 (% passing no. 4 & retained on No.200 sieve)

$F_1 > \frac{100-5}{2} = 47.5\%$ so the symbol is S (Sand)

Referring to the GSD curve we find $D_{10} = 0.18$ mm $D_{30} = 0.34$ mm $D_{60} = 0.71$ mm

$$C_u = \frac{D_{60}}{D_{10}} = 3.9 < 6; \; C_c = \frac{{D_{30}}^2}{D_{10}.D_{60}} \cong 0.91 \approx 1$$

as C_u & C_c does not meet the requirements of well- graded the soil is poorly graded , the symbol will be SP, but since % passing no. 200 sieve = 5% the soil will take a dual symbol since the soil is NP so the symbol is SM

so the symbol will be SP – SM .