Soil Mechanics Course Contents

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Tel.:

Prerequisite: Solid Mechanics, Engineering Mechanics and Fluid Mechanics

Text Book: *Principle of Geotechnical Engineering*, By B. M. Das, 6th edition, PWS Publishing Co.

Suggested Texts:

- *Craig's Soil Mechanics, By R. F Craig,* 7th edition, Spon Press.
- *Soil Mechanics, Basic Concepts and Engineering Applications*, By A. Aysen, 2002, A. A. Balkema Publishers.
- *Soil Mechanics*, By Arnold Verruijt, 2006, http://geo.verruijt.net.

Overview

A major specialty area within civil engineering, geotechnical engineering focuses on how soil and rock support and affect the performance of structure built on or below the earth's surface. Also, soil may be used as construction material. This course will be introducing the student to the basic principles that govern the behavior of soils, geotechnical properties of soil and other geotechnical works. The topics to be covered in this course are:

An understanding of these basic concepts is essential in the design of foundations for structures, retaining walls, tunnels, excavations, earth fills, stability of earth slopes, sanitary landfill, and environmental remediation projects. Specifically, a student completing this course will:

- **Understanding the basic principles of soil mechanics and geotechnical engineering.**
- **Learn the relevant terms and soil tests needed to describe and predict the behavior of a soil, permitting the student to work effectively with specialist in geotechnical engineering.**

- **Solve fundamentals problems related to the flow of pore water, compression and consolidation, and shear strength of soil as required in geotechnical design.**
- **Acquire the background knowledge needed to complete more advanced courses in geotechnical engineering (Foundation Eng., Advance soil mechanics and modeling).**

Homework Assignments

Appropriate homework will be assigned after covering a specific material. These assignments are due one week from the date they are assigned. Copying the assignments of other students is not a responsible behavior and will not be tolerated. Delay in submission the assignments will be graded in decrease as the time between the due dates.

Labs

Will be performing a number of experiments on different types of soils to improve our understanding of the material [i.e. water content, liquid and plastic limits, particle size distribution (Mechanical and hydrometer method),specific gravity of soil solids, compaction test, coefficient of permeability, consolidation test, direct shear test, unconfined and triaxial test] . Appropriate handouts on each test will be handed to the students ahead of time. Each student is expected to read the handouts before he comes to the lab. The students will work in one group or more depending on the number of the students in class. Every student is expected to turn in a lab report summarizing the work that was performed along with discussion for the results of the experiments. These reports are due by the time of the next experiment. The report has to be word-processed using a computer.

Exams

Intermediates exams will be on given dates later. Quizzes will be on given or sudden dates, that is depend on the decision of the instructor. The final exam will be comprehensive and will be at the time assigned by the department.

Grading

The work during the course will be cover 40% of the grade while the final exam covers the remaining 60 %.

Class evaluation	5%
Assignments	5%
Lab reports and exam	10%
Exam I	10%
Exam II	10%
Final Exam	60% (will be divided 50% theoretical and 10% experimental)

- **Soils**
  1. Origins of soils
  2. Soil particle size
  3. Clay Minerals
  4. Specific Gravity
  5. Mechanical analysis of soil
  6. Effective size, uniformity coefficient, and coefficient of gradation

- **Soil Composition**
  7. Weight-volume relations
  8. Relations among unit weight, e, w, and Gs
  9. Relative density
  10. Consistency of soil
  11. Liquidity index
  12. Activity
  13. Plasticity chart
  14. Soil Structure
  15. Problems

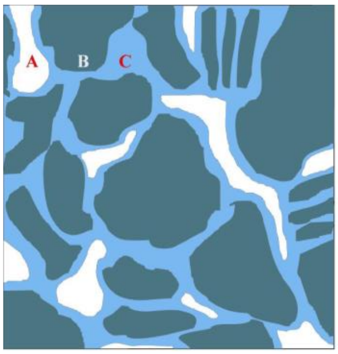
- **Classification of Soil**
  16. Textural Classification
  17. Classification by Engineering Behavior
  18. AASHTO and USCS classifications
  19. Problems

- **Soil Compaction**
  20. General Principals
  21. Standard and Modified Proctor
  22. Factors affecting compaction
  23. Field compaction
  24. Specification for field compactions
  25. Determinations of field unit weight of compaction
  26. Special compaction techniques
  27. Problems

Rock Cycle and Origin of Soil
(Das, Ch. 2)

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).



Where did soil come from?

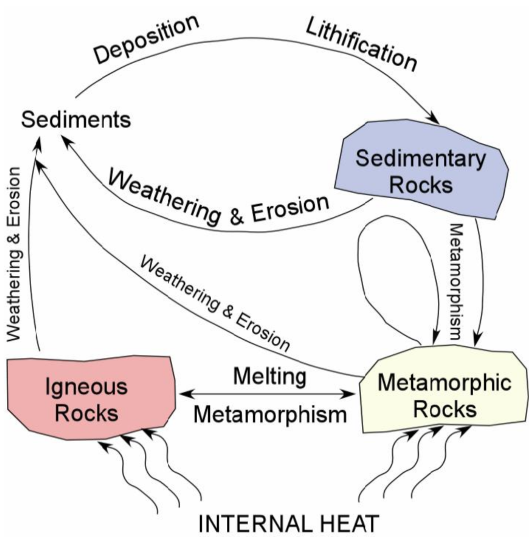
Soils are formed by weathering of rocks. The mineral grains that form the solid phase of a soil aggregate are the product of rock weathering.

Rock

In Geology, '**Rock**' is defined as the solid material forming the outer rocky shell or crust of the earth. There are three major groups of rocks by its origin:

1. Igneous Rocks: cooled from a molten state;
2. Sedimentary Rocks: deposited from fluid medium; e.g., products of weathering of other rocks in water;
3. Metamorphic Rocks: formed from pre-existing rocks by the action of heat and pressure.

Rock Cycles



Apparently, the igneous rock is the one far more essential and intrinsic since the other two types are relative secondary in origin.

Basic Mineralogy of Rocks

Rocks are formed of minerals. What is a mineral?

1. A naturally occurring chemical element or compound;
2. Formed by inorganic processes;
3. An ordered arrangement or pattern for its atoms–crystalline structure;
4. Possesses a definite chemical composition or range of compositions.

The opposite of mineral property is amorphous, i.e., the property of non-crystal, order-less property possessed by glass, volcanic glass, etc.; oil or coal can neither be regarded as minerals by their organic involvement.

- There are more than 2000 naturally occurred minerals have been discovered; only a bit more than 100 is common and used in college mineralogy.
- However, of the 100 common minerals only about 25 are abundant rock-forming minerals.
- The main types of minerals are: metallic minerals; nonmetallic minerals; carbonate minerals; sulfate minerals; sulfide minerals; silicate minerals; oxide minerals; clay minerals.

Comparison between surface and subsurface conditions

Subsurface	Surface
High temperature but constant at which minerals reach equilibrium	Low temperature, and highly variable
High confining pressure (stress)	Little or no confining pressure (stress)
Less water or no water	Abundant of water
No oxygen	Abundant of oxygen

- Rock at the surface will undergo changes, these changes are called Weathering.
- Weathering is the physical breakdown (disintegration) and chemical alteration (decomposition) of rocks to form soil or loose particles at or near Earth's surface.

Two types of weathering

Weathering: is the process of breaking down rocks by mechanical and chemical processes into smaller pieces.

Mechanical weathering: is the physical disintegration or degradation of rock pieces without a change in composition (size reduction).

Mechanical weathering processes include:

1. Freezing & thawing (frost wedge);
2. Differential expansion and contraction as temperature changes (in deserts or from forest fires), not all parts of a rock or all its minerals expand or contract by the same amount.

Chemical weathering: is decomposition whereby one mineral species is changed into another through various chemical processes. Water plays a major role, through:

1. Provide oxygen;
2. Provide mobility for moving ions.

Solution (or dissolution)

*Several common minerals dissolve in water.

Oxidation

Oxygen combines with iron-bearing silicate minerals causing "rusting".

Hydrolysis

Hydration-reaction between mineral and water.

Chemical weathering rate depends on:

1. Temperature;
2. Amount of surface area;
3. Availability of water or natural acid.

The transported soils may be classified into several groups, depending on their mode of transportation and deposition:

Glacial soils	formed by transportation and deposition of glaciers;
Alluvial soils	transported by running water and deposited along streams;
Lacustrine soils	formed by deposition in quiet lakes;
Marine soils	formed by deposition in the sea;
Aeolian soils	transported and deposited by wind;
Colluvial soils	formed by movement of soil from its original place by gravity, such as during landslides.

Soil-Particles Size
(Das, Ch. 2)

Engineering Definition of Soil:
Soil is the earth material that can be disaggregated in water by gentle agitation.

Soil Particles
The description of the grain size distribution of soil particles according to their texture (particle size, shape, and gradation).

Major textural classes include:
Gravel particle size >4.75 mm;
Sand particle size (0.075 –4.75) mm;
Silt particle size (0.005 –0.075) mm;
Clay particle size < 0.005 mm.

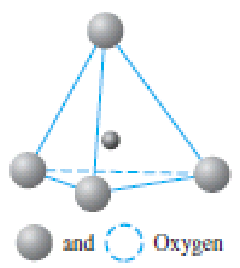
Furthermore, **gravel and sand** can be roughly classified as **coarse grained soils**, while **silt and clay** can be classified as **fine textures soils**.

For engineering purposes, soils can also be divided into **cohesive** (fine textured soils) and **non-cohesive** soils (coarse grained soils). Cohesive soil contains clay minerals and possesses plasticity.

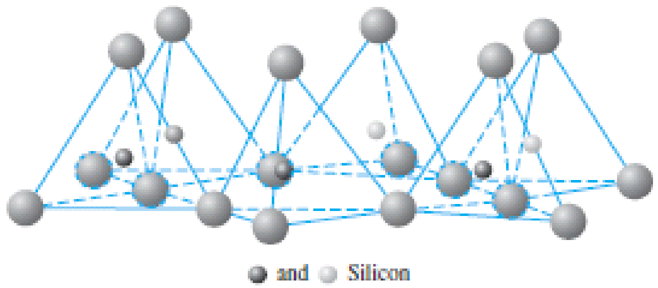
Clay Minerals
Clay minerals are complex aluminum silicates composed of two basic units:

1- Silica Tetrahedron
- Each tetrahedron unit consists of four oxygen atoms surrounding a silicon atom.
- The combination of tetrahedral silica units gives a silica sheet. Three oxygen atoms at the base of each tetrahedron are shared by neighboring tetrahedra.

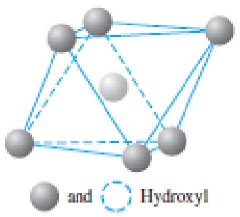
2- Alumina Octahedron
- The octahedral units consist of six hydroxyls surrounding an aluminum atom.
- The combination of the octahedral aluminum hydroxyl units gives an octahedral sheet (gibbsite sheet).
- Sometimes magnesium replaces the aluminum atoms in the octahedral units; in this case, the octahedral sheet is called a brucite sheet.



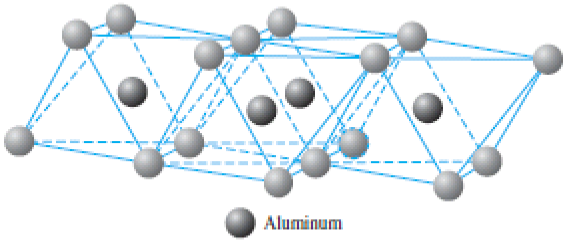
Silica Tetrahedron



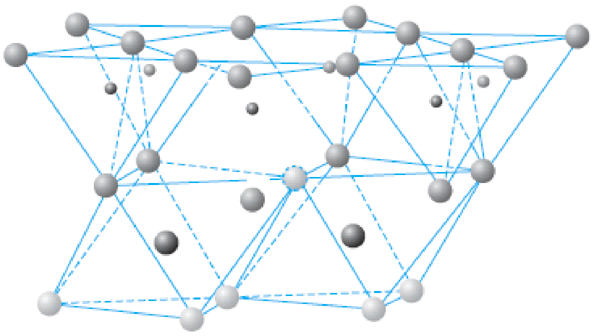
Silica Sheet



Alumina Octahedron



Gibbsite Sheet



Elemental Silica-Gibbsite Sheet

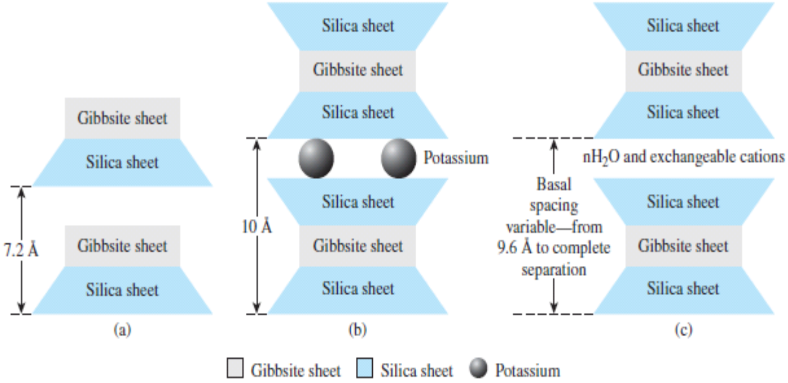
The three important clay minerals are:

kaolinite: consists of repeating layers of elemental silica-gibbsite sheets in a 1 :1 lattice. Each layer is about 7.2 Å thick. The layers are held together by hydrogen bonding.

- Kaolinite occurs as platelets, each with a lateral dimension of 1000 to 20,000 Å and a thickness of 100 to 1000 Å.
- The surface area per unit mass is defined as specific surface. The surface area of the kaolinite particles per unit mass is about 15 m^2/g.

Illite: consists of a gibbsite sheet bonded to two silica sheets-one at the top and another at the bottom. It is sometimes called clay mica.

- The illite layers are bonded by potassium ions.
- Illite particles generally have lateral dimensions ranging from 1000 to 5000 Å and thicknesses from 50 to 500 Å.
- The specific surface of the particles is about 80 m^2/g.



(a) kaolinite; (b) illite; (c) montmorillonite

Montmorillonite: has a structure similar to that of illite-that is, one gibbsite sheet sandwiched between two silica sheets.

- In montmorillonite there is isomorphous substitution of magnesium and iron for aluminum in the octahedral sheets.
- Particles of montmorillonite have lateral dimensions of 1000 to 5000 Å and thicknesses of 10 to 50 Å.
- The specific surface is about 800 m^2/g.

Particle size determination

•Sieving Analysis: used for particles sizes > 0.075 mm in diameter;
•Hydrometer test: used for smaller particles (φ< 0.075 mm), analysis based on Stoke's Law (velocity proportional to diameter).

- For soils with both fine and coarse grained materials a combined analysis is made using both the sieve and hydrometer procedures.

Sieving Test

Sieve test consists of shaking the soil sample through a set of sieves, the test used for the grain size greater than 0.075 mm (75 microns).

Standard Sieve Sizes

Sieve No.	Sieve opening (mm)
4	4.75
10	2.00
20	0.85
40	0.425
60	0.25
100	0.15
200	0.074

Procedure of Sieve Analysis

1. The total mass of soil sample (ΣM) used in sieve test;
2. Determine the mass of soil retained on each sieve and the pan at end of test (i.e., M_1, M_2, M_3, ….., M_n, and M_p);
3. The sum of soil mass retained on each sieve plus the mass in the pan should be equal to the total mass ($\Sigma M= M_1+M_2+M_3+\ldots +M_n+M_p$);
4. Determine the cumulative mass of soil retained above each sieve, for the i^{th} sieve we have $\Sigma M_i= M_1+M_2+M_3+\ldots +M_i$;
5. The mass of soil passing the i^{th} sieve is $\Sigma M-\Sigma M_i$;
6. The percent of soil passing the i^{th} sieve (percent finer) is:

$$F = \frac{\sum M - \sum Mi}{\sum M} X\, 100$$

Example: If you have a soil sample with a weight of 150 gm, after sieving you get the following result.

Sieve No.	Sieve Opening (mm)	Retained Weight, gm	Percentage of Retained %	Accumulated Retained Weight %	Percentage Finer %
4	4.75	30.0			
20	0.85	40.0			
60	0.25	50.0			
100	0.15	20.0			
200	0.074	10.0			

Hydrometer Analysis

The hydrometer test uses Stokes law (for the velocity of a free falling sphere in suspension) to determine grain size smaller than 0.075 mm (sieve no.200). In the hydrometer analysis, the soil passing from sieve no.200 is placed in suspension and by use of Stokes' equation the equivalent particle size and percent of soil in suspension are computed.

Stoke's Law

A sphere falling freely through a liquid of infinite extent will accelerate rapidly to a certain maximum velocity and will continue at that velocity as long as conditions remain the same.

$$\mathbf{v} = \frac{\rho_s - \rho_w}{18\eta} \text{ x } D^2$$

where
v: velocity of the particle;
ρ_s: density of soil particles;
ρ_w: density of water;
η: viscosity of water;
D: diameter of soil particles.

From the Stokes' equation, rearranging the factors we can get

$$D = \sqrt{\frac{18\eta v}{\rho_s - \rho_w}} = \sqrt{\frac{18\eta}{\rho_s - \rho_w}} \sqrt{\frac{L}{t}}$$

With

$$\rho_s = G_s \rho_w$$

Where **Gs** is the specific gravity of the soil particle and defined as the ratio of the unit weight of a given material to the unit weight of water. The expected value of Gs for different types of soils are given in table below:

Type of Soil	Gs
Sand	2.65 -2.67
Silty sand	2.67–2.70
Inorganic clay	2.70 –2.80
Soils with mica or iron	2.75 –3.00
Organic soils	< 2.00

so we can write,

$$\mathbf{D} = \sqrt{\frac{18\eta}{(G_s - 1)\rho_w}}\sqrt{\frac{L}{t}}$$

With the use of the SI units: the viscosity η in g . sec/cm^2 and ρ_w =1 g/cm^3, the length L in cm, time t in minute, and D in mm, we can get

$$\mathbf{D(mm)} = \sqrt{\frac{30\eta}{(G_s - 1)}}\sqrt{\frac{L}{t}} = K\sqrt{\frac{L(cm)}{t(min)}}$$

Since both viscosity and specific gravity of soil particles are temperature dependent, so does parameter K.

The value of L (cm) for ASTM 152H hydrometer can be given by the expression:

$$L = L_1 + \frac{1}{2}\left(L_2 - \frac{V_b}{A}\right)$$

where
L_1: the length of the hydrometer stem suspended in solution;
L_2: the length of the hydrometer bulb=14 cm;
V_b: the volume of the hydrometer bulb=67 cm^3;
A: cross-section area of the sedimentation cylinder=27.8 cm^2.
The value of L_1 is 10.5 cm for a reading of R=0 and 2.3 cm for a reading of R=50. Hence, for any reading R:

$$L_1 = 10.5 - \frac{10.5 - 2.3}{50}R = 10.5 - 0.164R\ (cm)$$

- ❖ Stokes' Law is applicable to spheres varying from 0.02 mm to 0.0002 mm in diameter.

- ❖ Inaccuracies for using the Stokes’ equation to determine the particle size occur due to the following factors:

1) Soil particles are not spheres;
2) The fluid is not of infinite extent;
3) Turbulence caused by larger particles falling.

- ➢ The change of K values with temperature are given in Table below.

Temperature (°C)	G_s 2.45	2.50	2.55	2.60	2.65	2.70	2.75	2.80
16	0.01510	0.01505	0.01481	0.01457	0.01435	0.01414	0.01394	0.01374
17	0.01511	0.01486	0.01462	0.01439	0.01417	0.01396	0.01376	0.01356
18	0.01492	0.01467	0.01443	0.01421	0.01399	0.01378	0.01359	0.01339
19	0.01474	0.01449	0.01425	0.01403	0.01382	0.01361	0.01342	0.01323
20	0.01456	0.01431	0.01408	0.01386	0.01365	0.01344	0.01325	0.01307
21	0.01438	0.01414	0.01391	0.01369	0.01348	0.01328	0.01309	0.01291
22	0.01421	0.01397	0.01374	0.01353	0.01332	0.01312	0.01294	0.01276
23	0.01404	0.01381	0.01358	0.01337	0.01317	0.01297	0.01279	0.01261
24	0.01388	0.01365	0.01342	0.01321	0.01301	0.01282	0.01264	0.01246
25	0.01372	0.01349	0.01327	0.01306	0.01286	0.01267	0.01249	0.01232
26	0.01357	0.01334	0.01312	0.01291	0.01272	0.01253	0.01235	0.01218
27	0.01342	0.01319	0.01297	0.01277	0.01258	0.01239	0.01221	0.01204
28	0.01327	0.01304	0.01283	0.01264	0.01244	0.01225	0.01208	0.01191
29	0.01312	0.01290	0.01269	0.01249	0.01230	0.01212	0.01195	0.01178
30	0.01298	0.01276	0.01256	0.01236	0.01217	0.01199	0.01182	0.01169

[a]After ASTM (1999)

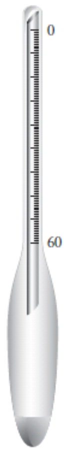


Figure 2.23
ASTM 152H hydrometer
(*Courtesy of ELE International*)

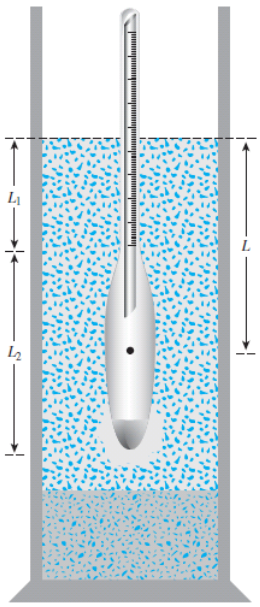


Figure 2.24 Definition of *L* in hydrometer test

ASTM 152H Hydrometer and the definition of L (Das, 2008).

Gradation

Gradation is a measure of the distribution of a particular soil sample.

- ❖ Larger gradation means a wider particle size distribution and soil can be classified as well graded, poorly graded or gap-graded.

Effective Size, D_{10}

D_{10} represents a grain diameter for which 10% of the sample will be finer than it. Using another word, 10% of the sample by weight is smaller than diameter D_{10}.

Hazen's approximation (an empirical relation between hydraulic conductivity with grain size).

$$k(cm/s) = c\, D_{10}^2$$

Where D_{10} is in millimeters and c is constant varies from 1.0-1.5.

Uniformity coefficient, Cu

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

Where D_{60} is the diameter for which 60% of the sample is finer than D_{60}.

- *Apparently, larger Cu means the size distribution is wider and vice versa. Cu= 1 means uniform, all grains are in the same size, such as dune sands.*

Coefficient of gradation, Cz (Coefficient of curvature, Cc)

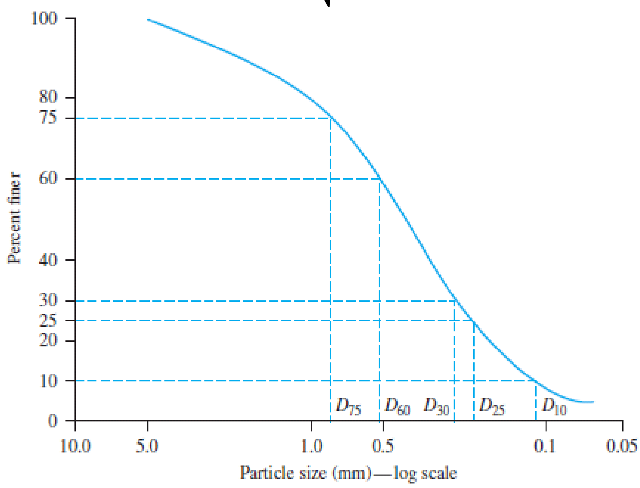
$$C_z = \frac{D_{30}^2}{D_{60} \times D_{10}}$$

- *A soil is to be well graded if the coefficient of gradation Cz between 1 and 3 and Cu greater than 4 for gravels and 6 for sands.*

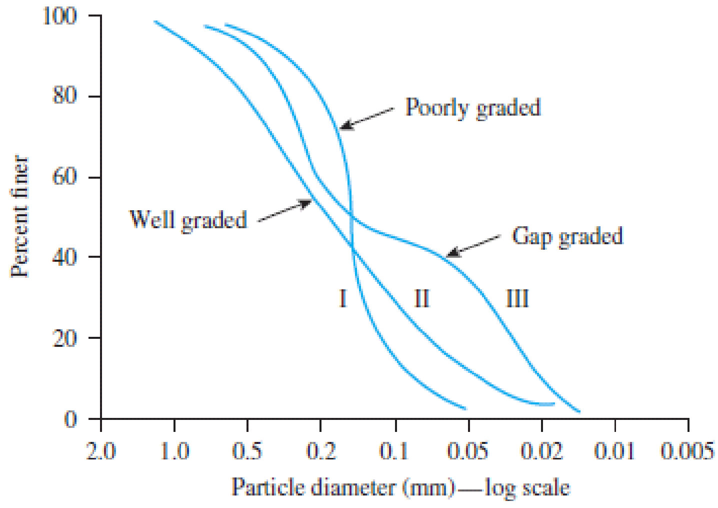
Sorting Coefficient S_0

Another parameter for measuring uniformity used mostly by geologists.

$$S_o = \sqrt{\frac{D_{75}}{D_{25}}}$$



- The particle size distribution curve shows not only the range of particle sizes present in a soil, but also the type of distribution of various sizes particles.



- **Curve I** represents a poorly graded soil (most grains have the same size);
- **Curve II** represents a well graded soil (wide range distribution of the particle sizes);
- **Curve III** represents a gab graded soil (have a combination of two or more uniformly graded fractions).

Particle Shape

The shape of particles has significant influence on the physical properties of a given soil. The particle shape can be divided into three major categories:

Bulky particles: are mostly formed by mechanical weathering of rock and minerals (angular, subangular, rounded, and subrounded). The angularity, A, is defined as:

$$\boldsymbol{A = \frac{Average\ radius\ of\ corners\ and\ edges}{maximum\ radius\ of\ the\ inscribed\ sphere}}$$

The sphericity of bulky particles is defined as:

$$\boldsymbol{S = \frac{D_e}{L_p}}$$

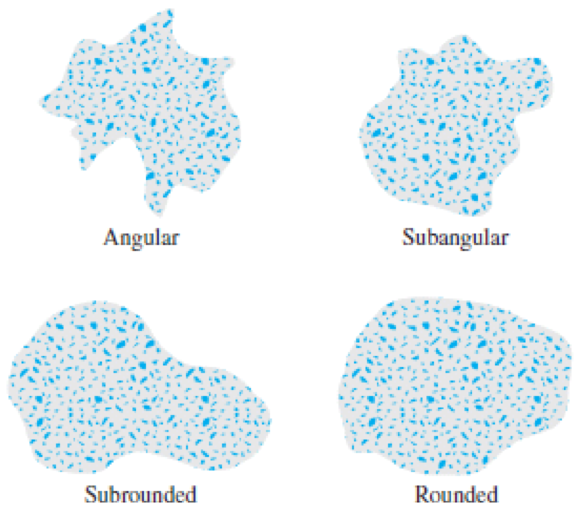
where

D_e : is the equivalent diameter of the particle= $\sqrt[3]{\frac{6V}{\pi}}$;

V : is the volume of particle
L_p : is the length of particle

Flaky particles: have very low sphericity--usually 0 .01 or less. These particles are predominantly clay minerals.

Needle-shaped particles: are much less common than the other two particle types. (Coral deposits and attapulgite clays).



Example

Sieve analysis test was conducted on 650 grams of soil. The results are as follows:

Sieve No.	9.53	4	10	20	40	100	200	Pan
Opening, mm	9.53	4.75	2	0.85	0.425	0.15	0.075	-
Mass retained, gm	0	53	76	73	142	85	120.5	99.8

Calculate the % finer and plot the particle-size distribution curve. Extract the amount of coarse-grained soil (particle sizes $\geq$0.075 mm) and the amount of fine-grained soil (particle sizes $\leq$0.075 mm). Also, find the D_{10}, Cu, Cz, So and k in cm/sec.

Solution:

Weight-Volume Relationships
(Das, Ch. 3)

For a general discussion we have:

Weight, W: $W = Mg$
M=mass,
g= gravity acceleration = 9.81 m/s^2, 32.17405 ft/s^2

Density, ρ: $\rho = M/V$
V=volume.

Unit weight, γ: $\gamma = W/V$

So that

$$\gamma = \frac{W}{V} = \frac{M\,g}{V} = \rho\,g$$

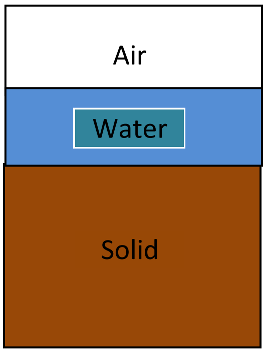
Unit weight

Is the product of density with gravity acceleration (g). It is the gravitational force caused by the mass of material within a unit volume.

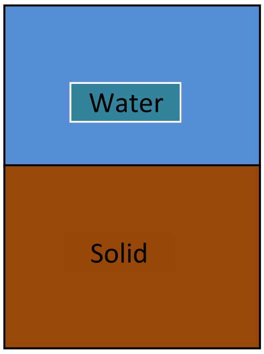
Soil Models

Naturally occurred soils always consist of solid particles, water, and air, so that soil has three phases: solid, liquid and gas.

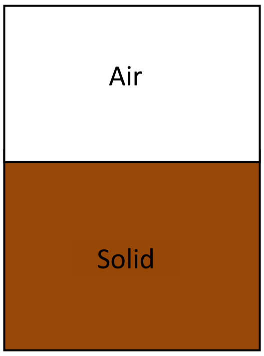
a) Three Phase (Partially Saturated Soil).
b) Two Phase (Fully Saturated Soil).
c) Two Phase (Dry Soil).



Partially Saturated Soil
a

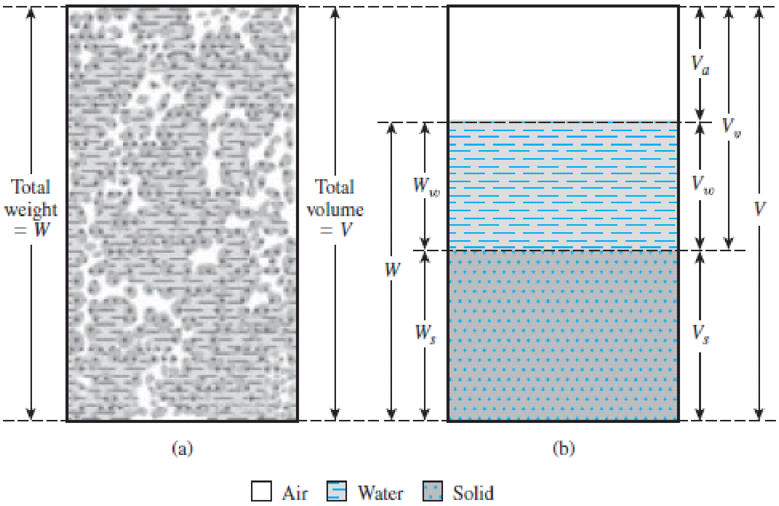


Fully Saturated Soil
b



Dry Soil
c

Three Phase Diagram



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

It is convenient to assume the volume of the solid phase is unity (1) without lose generality.

$$M = M_s + M_w$$

and

$$W = W_s + W_w$$

Void ratio: $e = V_v/V_s$

Porosity: $n = V_v/V$

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

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

Apparently, for the same material we always have e > n.

Degree of saturation (S):

$$S = \frac{V_w}{V_v} x\, 100$$

Moisture content (Water content): is measured by the ratio of weight (so that **w** can be greater than 100%).

$$w = W_w/W_s \qquad \& \qquad W_w = V\,\gamma_w$$

Definition of Unit Weight Types

i- Total unit weight, γ_t:

(moisture unit weight, wet unit weight, bulk unit weight)

$$\gamma_t = \frac{W}{V} = \frac{W_s + W_w}{V} = \frac{W_s[1 + (W_w/W_s)]}{V} = \frac{W_s(1 + w)}{V}$$

ii- Dry unit weight γ_d:

$$\gamma_d = \frac{W_s}{V} = \frac{\gamma_t}{1 + w} \quad \because \ (W_s + W_w) > W_s \quad \therefore \quad \gamma_d < \gamma_t$$

iii- Saturated unit weight γ_{sat}:

(when saturation, S=1)

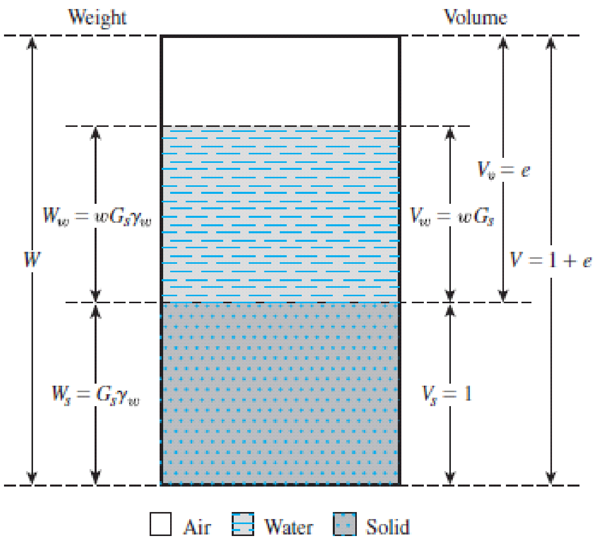
$$\gamma_{sat} = \frac{W}{V} = \frac{W_s + W_w}{V}$$

We can write the same expressions for the density of soil as follows:

$$\rho_t = \frac{M}{V}, \qquad \rho_d = \frac{M_s}{V}$$

Relationships among γ, e, w, and Gs

Consider the soil element shown below; the volume of soil solid is 1.



$$\gamma_s = G_s\gamma_w, \ V_s = 1 \ \rightarrow \ W_s = G_s\gamma_w$$

$$W_w = w\,W_s = wG_s\gamma_w$$

$$\gamma_t = \frac{W}{V} = \frac{W_s + W_w}{V} = \frac{G_s\gamma_w + wG_s\gamma_w}{1 + e} = \frac{(1 + w)G_s\gamma_w}{1 + e}$$

and

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

$$\gamma_w = \frac{W_w}{V_w} \rightarrow V_w = \frac{W_w}{\gamma_w} = \frac{wG_s\gamma_w}{\gamma_w} = G_s w$$

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

$$S.e = w\,G_s$$

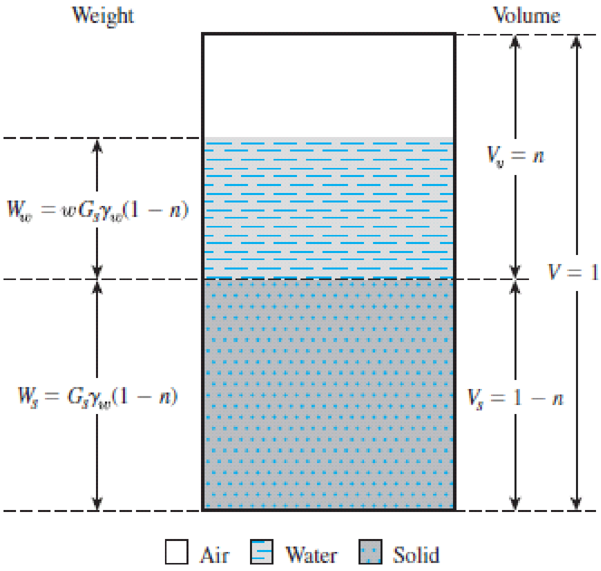
For saturated Soil

$$S = 1 \rightarrow e = w\,G_s$$

$$\gamma_{sat} = \frac{W}{V} = \frac{W_s + W_w}{V} = \frac{G_s\gamma_w + e\gamma_w}{1+e} = \frac{(G_s + e)\gamma_w}{1+e}$$

Relationships among γ, n, w, and Gs

Consider a soil element shown below, has total volume equal to unity.



$$\gamma_d = \frac{W_s}{V} = \frac{G_s\gamma_w(1-n)}{1} = G_s\gamma_w(1-n)$$

$$\gamma_t = \frac{W_s + W_w}{V} = \frac{G_s\gamma_w(1-n) + w\,G_s\gamma_w(1-n)}{1} = G_s\gamma_w(1-n)(1+w)$$

$$\gamma_{sat} = \frac{W_s + W_w}{V} = \frac{G_s\gamma_w(1-n) + n\gamma_w}{1} = [G_s(1-n) + n]\gamma_w$$

when S=1, the water content is:

$$w = \frac{W_w}{W_s} = \frac{n\gamma_w}{G_s\gamma_w\,(1-n)} = \frac{n}{G_s(1-n)} = \frac{e}{G_s}$$

Several other forms of relationships that can be obtained for γ, γ_d, and γ_{sat} are given in Table below.

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}	$\gamma_d(1+w_{sat})$

Relative Density

-It indicates the in situ denseness or looseness of granular soil.

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}}$$

D_r: is the relative density, usually given as percentage;
e : is the in situ void ratio of the soil;
e_{max}: is the void ratio of the soil in the loosest state;
e_{min}: is the void ratio of the soil in the densest state.

- In terms of the porosity

$$D_r = \frac{(1-n_{min})(n_{max}-n)}{(n_{max}-n_{min})(1-n)}$$

- In terms of unit weight

$$D_r = \left[\frac{\gamma_d - \gamma_{d(min)}}{\gamma_{d(max)} - \gamma_{d(min)}}\right]\left[\frac{\gamma_{d(max)}}{\gamma_d}\right]$$

$\gamma_{d(min)}$: is the dry unit weight in the loosest condition (at a void ratio of e_{max});
$\gamma_{d(max)}$: is the dry unit weight in the densest condition (at a void ratio of e_{min});
γ_d: is the in situ dry unit weight (at void ratio of e).

- In terms of density

$$D_r = \left[\frac{\rho_d - \rho_{d(min)}}{\rho_{d(max)} - \rho_{d(min)}}\right]\left[\frac{\rho_{d(max)}}{\rho_d}\right]$$

- Qualitative description of granular soil deposits

Relative Density %	Description
0-15	Very loose
15-50	Loose
50-70	Medium
70-85	Dense
85-100	Very dense

Consistency of Soil
Atterberg's Limits
(Das, Ch. 3)

Soil Consistency

Soil consistency describes the degree and kind of cohesion and adhesion between the soil particles as related to the resistance of the soil to deform or rupture.

- ❖ Since the consistency varies with moisture content, the consistency can be described as dry consistency and moist consistency.
- ❖ Consistency largely depends on soil minerals and the water content.

Cohesion & Adhesion

- ➢ Cohesion is the attraction of one water molecule to another resulting from hydrogen bonding (water-water bond).
- ➢ Adhesion is the attraction of a water molecule to a non-water molecule (water-solid bond).

Stickiness

Stickiness is the capacity of soil to adhere to other objects.

- ❖ Non-Sticky–little or no soil adheres to fingers after release of pressure;
- ❖ Slightly Sticky – soil adheres to both fingers after release of pressure with little stretching on separation of fingers;
- ❖ Moderately Sticky–soil adheres to both fingers after release of pressure with some stretching on separation of fingers;
- ❖ Very Sticky-soil adheres firmly to both fingers after release of pressure with stretches greatly on separation of fingers.

Non-Sticky

Slightly- Sticky

Very Sticky

Plasticity

Plasticity property describes the response of a soil to change in moisture content.

- Strength decreases as water content increases;
- Soils swell-up when water content increases.

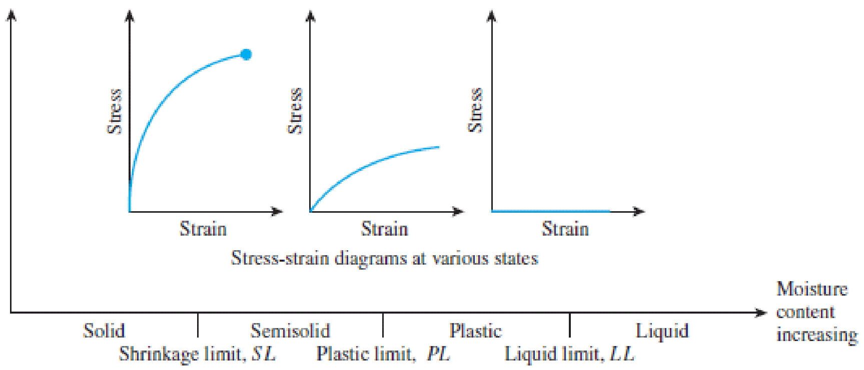
Atterberg's Limits

- Atterberg's limits are the limits of water content and important to describe the consistency of fine-grained soils.
- Four states are used to describe the soil consistency; solid, semi-solid, plastic and liquid.

Liquid Limit (LL) is the water content at which soil begins to behave as a liquid material and begins to flow (normally below 100).

Plastic Limit (PL) is the water content at which soil begins to behave as a plastic material (normally below 40).

Shrinkage Limit (SL) is the water content at which no further volume change occurs with further reduction in water content.

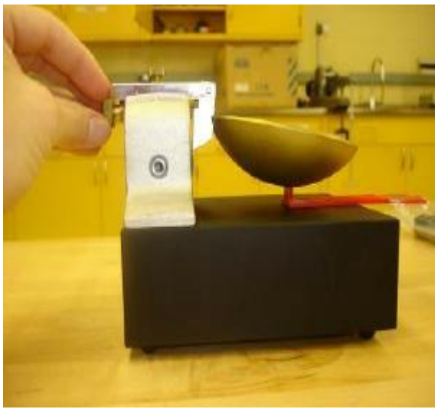


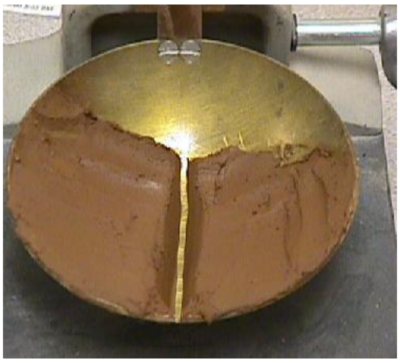
Liquid Limit (LL) Test

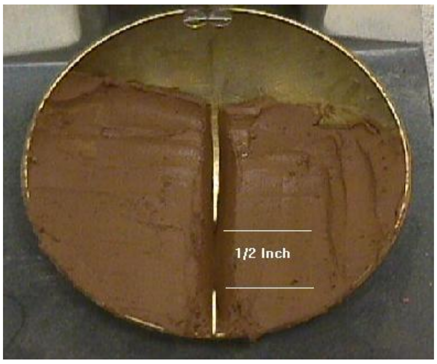
In the lab, the LL is defined as the water content required closing a 2mm wide groove in a soil sample for a distance of 0.5 in long after 25 blows.

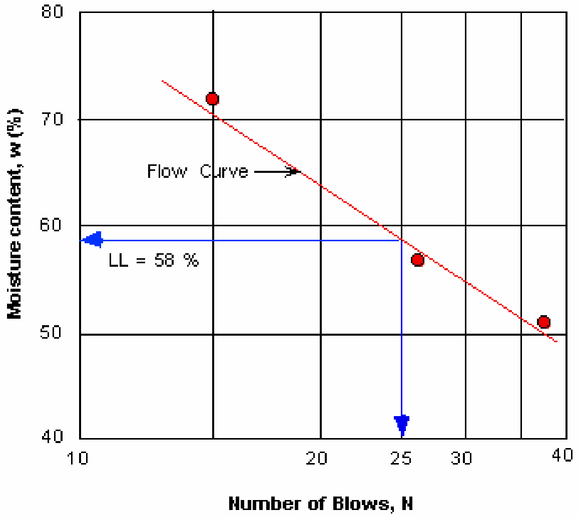
- ASTM D 4318.
- Equipment: Casagrande liquid limit device**.**
- The procedure of test is:

1) Take 150g air dried soil passing No.40 sieve;
2) Add 20% of water and mix;
3) Place a small sample of soil in LL device;
4) Cut a groove of 2mm width at the base;
5) Run the device and count the number of blows, N;
6) Stop when the groove in the soil close through a distance of 0.5in;
7) Take a sample and find the moisture content;
8) Run the test three times [N~(10-20), N~(20-30) and N~(35-45)];
9) Plot number of blows versus moisture content and determine the liquid limit (LL) corresponding to N=25 **blows.**







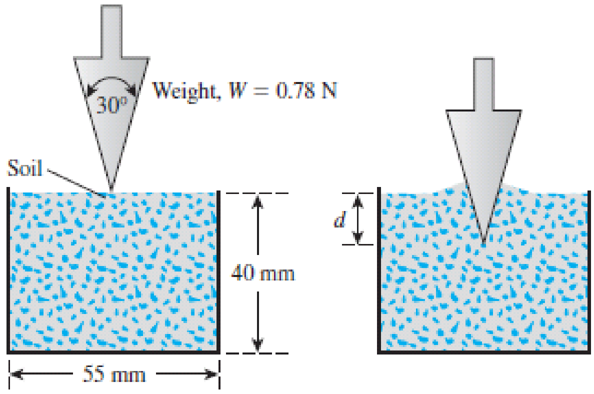


The slope of the flow line is defined as the flow index (I_F) and may be written as:

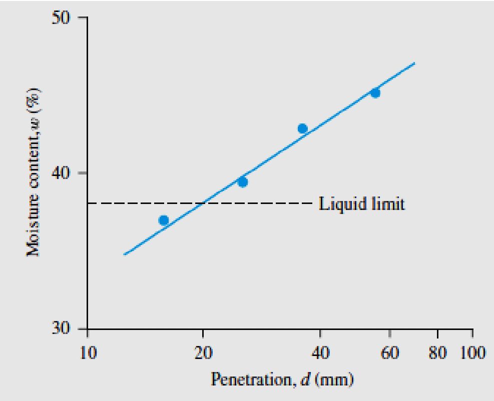
$$I_F = \frac{\omega_1 - \omega_2}{\log \frac{N_2}{N_1}}$$

Another method of determining liquid limit is the fall cone method (British Standard - BS1377).

- In this test the liquid limit is defined as the moisture content at which a standard cone of apex angle 30° and weight of 0.78 N will penetrate a distance d = 20 mm in 5 seconds when allowed to drop from a position of point contact with the soil surface.



- Due to the difficulty in achieving the liquid limit from a single test, four or more tests can be conducted at various moisture contents to determine the fall cone penetration, d.
- A semilogarithmic graph can then be plotted with moisture content (w) versus cone penetration d. The plot results in a straight line. The moisture content corresponding to d = 20 mm is the liquid limit.

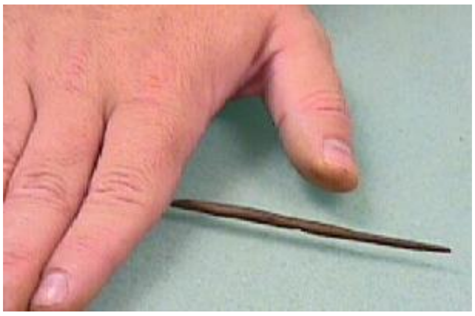


Plastic Limit (PL)

In the lab, the plastic limit (PL) is defined as the water content at which the soil when rolled into threads of 3.2mm (1/8 in) in diameter, will crumble.

- ASTM D-4318.
- The procedure of test is:

1) Take 20g of soil passing No.40 sieve into a dish;
2) Add water and mix thoroughly;
3) Prepare several ellipsoidal-shaped soil masses by quizzing the soil with your hand;
4) Roll the soil until the thread reaches 1/8 in;
5) Continue rolling until the thread crumbles into several pieces;
6) Determine the water content of about 6g of the crumbled soil.


Plasticity Index, PI

is the difference between the liquid limit and plastic limit of a soil.

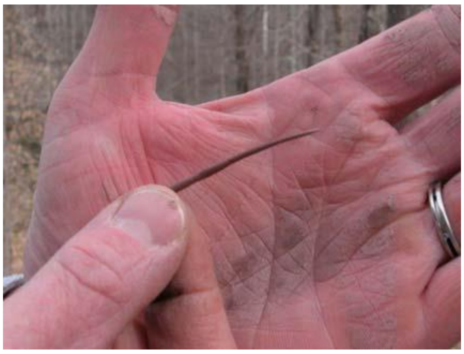
$$PI = LL - PL$$

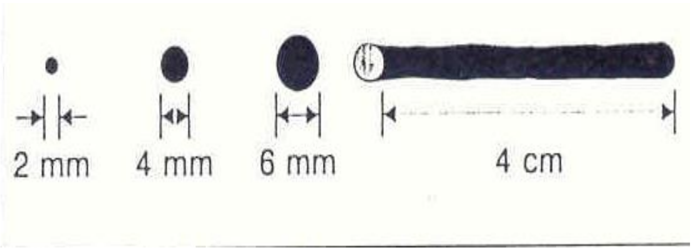
Plasticity Class

Burmister (1949) classified the plasticity index in a qualitative manner as follows:

PI	Description
0	Nonplastic (NP)
1-5	Slightly plastic
5-10	Low plasticity
10-20	Medium plasticity
20-40	High plasticity
>40	Very high plasticity

- Non-Plastic: will not form a 6mm diameter and 4cm long wire, or if formed, cannot support itself if held on end;
- Slightly Plastic: 6mm diameter and 4cm long wire which supports itself, but 4mm diameter and 4cm long does not support itself;
- Moderately Plastic: 4mm diameter and 4cm long wire which supports itself, but 2mm diameter and 4cm long wire does not support itself;
- Very Plastic: 2mm diameter and 4cm long wire support itself.





Shrinkage Limit (SL)

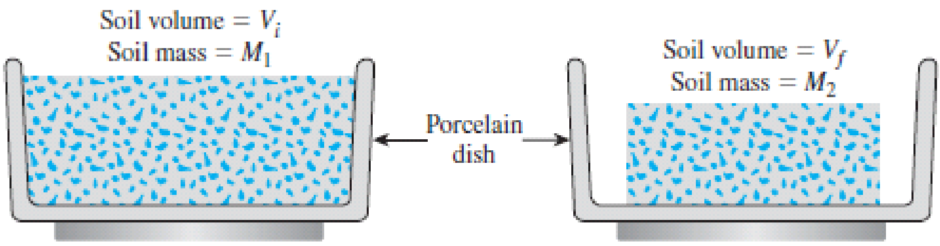
In the lab, the moisture content, in percent, at which the volume of the soil mass ceases to change.

- ASTM Test Designation D-427;
- The procedure of test is:

1) Prepare the soil sample;
2) Prepare a porcelain dish about 44 mm (1.75 in.) in diameter and about 12.7 mm (0.5 in.) high. The inside of the dish is coated with petroleum jelly and is then filled completely with wet soil;
3) The mass of the wet soil inside the dish is recorded;
4) The soil pat in the dish is then oven-dried;
5) The volume of the oven-dried soil pat is determined by the displacement of mercury.

$$SL = w_i(\%) - \Delta w\ (\%)$$

where
w_i = initial moisture content when the soil is placed in the shrinkage limit dish;
Δw = change in moisture content (that is, between the initial moisture content and the moisture content at the shrinkage limit).



$$w_i(\%) = \frac{M_1 - M_2}{M_2} \times 100$$

where
M_1 = mass of the wet soil pat at the beginning of the test (g).
M_2 = mass of the dry soil pat (g).

Also,

$$\Delta w(\%) = \frac{(V_i - V_f)\rho_w}{M_2}(100)$$

where
V_i = initial volume of the wet soil pat (that is, inside volume of the dish, cm^3).
V_f = volume of the oven-dried soil pat (cm^3).
ρ_w = density of water (g/cm^3).

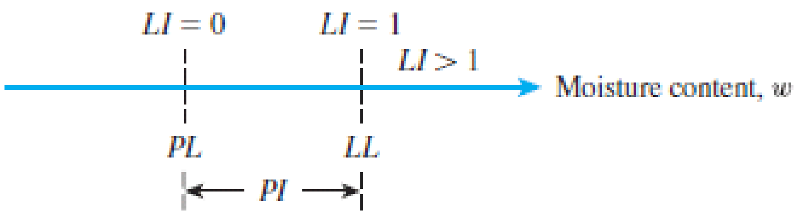
$$SL = \frac{M_1 - M_2}{M_2}(100) - \frac{V_i - V_f}{M_2}(\rho_w)(100)$$

Liquidity Index (LI)

The relative consistency of a cohesive soil in the natural state can be defined by a ratio called the liquidity index (LI).

$$LI = \frac{w - PL}{LL - PL}$$

Where w is the in situ moisture content.



Another index that is commonly used for engineering purposes is the consistency index (CI), which may be defined as:

$$CI = \frac{LL - w}{LL - PI}$$

Activity

Is the slope of the line correlating PI and % finer than 2 μm.

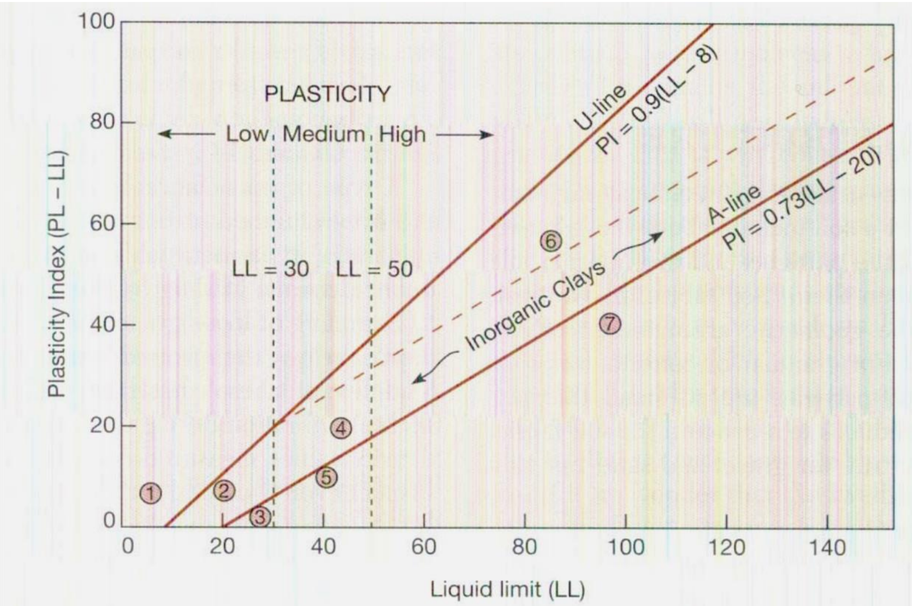
- Activity is used as an index for identifying the swelling potential of clay soils.
- Skempton (1953) defined activity as follows:

$$A = \frac{PI}{\%\ of\ clay\ size\ fraction\ by\ weight}$$

Plasticity Chart

Engineers have used liquid and plastic limits extensively for the correlation of several physical soil parameters as well as for soil identification.

Casagrande (1932) studied the relationship of PI to the LL of a wide variety of natural soils. On the basis of the test results, he proposed a plasticity chart as shown in Figure below.



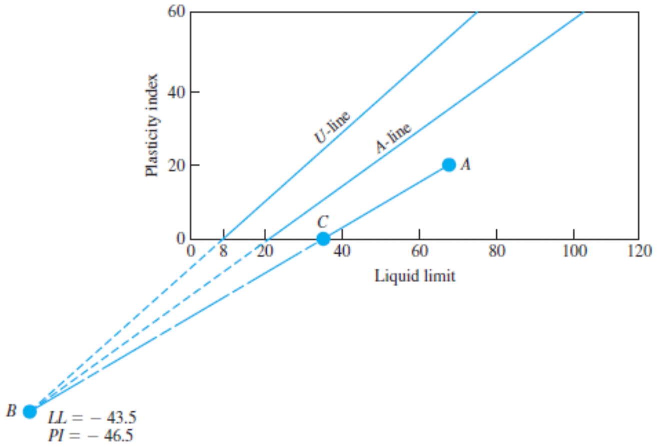
Key:
1) Cohesionless soils
2) Inorganic clays, low plasticity
3) Inorganic silts, low compressibility
4) Inorganic clays, medium plasticity
5) Inorganic silts and organic clays, medium compressibility
6) Inorganic clays, high plasticity
7) Inorganic silts and organic clays, high compressibility

A-line: separates the inorganic clays from the inorganic silts.
U-line: is approximately the upper limit of the relationship of the PI to the LL for any currently known soil.

C: is inorganic clay; **M:** is inorganic silt; **O:** is organic silt or clay; **S:** is sand; **G:** is gravel.

- Casagrande has suggested that the SL of a soil can be approximately determined if its PI and LL are known.

a. Plot the PI against the LL of a given soil such as point A in on the plasticity chart;
b. Project the A-line and the U-line downward to meet at point B. Point B will have the coordinates of LL=43.5 and PI=46.4;
c. Join points B and A with a straight line. This will intersect the liquid limit axis at point C. The point C is the estimated shrinkage limit.



Soil Structure

Soil structure is the geometric arrangement of soil particles with respect to one another.

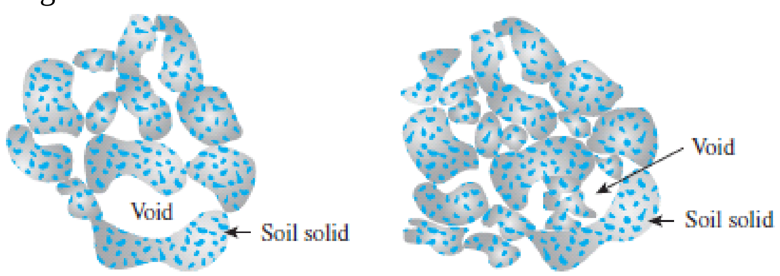
- The factors affect the structure are the shape, size, and mineralogical composition of soil particles, and the nature and composition of soil water.

Structures in Cohesionless Soil

The structures of cohesionless soils can be divided into two major categories:

a- Single grained

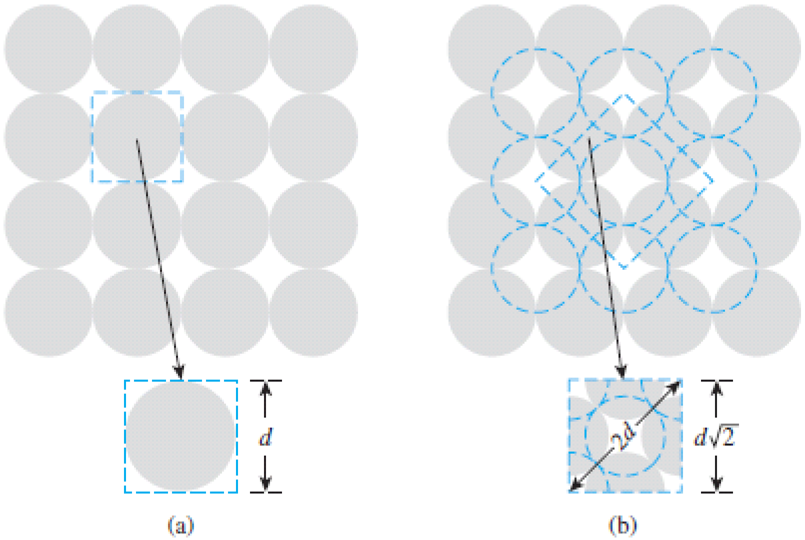
soil particles are in stable positions, with each particle in contact with the surrounding ones. The shape and size distribution of the soil particles and their relative positions influence the denseness of packing.



Single-grained structure

Loose Dense

Let us consider the mode of packing of equal spheres shown in Figure below.



Very loose packing, e=0.91 Very dense packing, e=0.35

The void ratio can be calculated as:

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

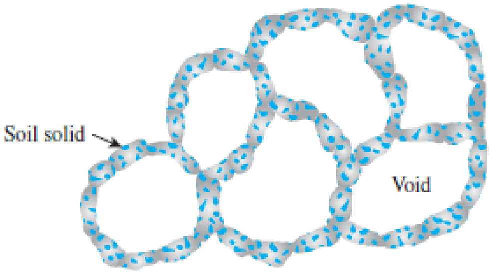
where
V = volume of the cube;
Vs = volume of sphere (i.e., solid) inside the cube.
For the very loose packing, V = d^3 and Vs = $\pi d^3/6$, so:

$$e = \frac{d^3 - \left(\frac{\pi d^3}{6}\right)}{\left(\frac{\pi d^3}{6}\right)} = 0.91$$

b- Honeycombed

In the honeycombed structure, fine sand and silt form small arches with chains of particles and have large void ratios.

- However, under a heavy load or when subjected to shock loading, the structure breaks down, which results in a large amount of settlement.



Honeycombed Structure

Structures in Cohesive Soils

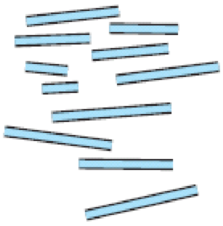
There are two types of forces that act between clay particles suspended in water.

1- The negative charge on the surface of the clay particles and the diffuse double layer surrounding each particle. When two clay particles in suspension come close to each other, the tendency for interpenetration of the diffuse double layers results in repulsion between the particles.

2- An attractive force exists between the clay particles that is caused by van der Waals forces and is independent of the characteristics of water.

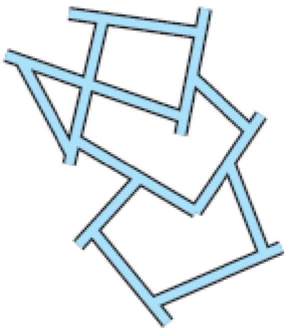
- ❖ Both repulsive and attractive forces increase with decreasing distance between the particles, but at different rates.
- ❖ When the spacing between the particles is very small, the force of attraction is greater than the force of repulsion.

The sediment formed by the settling of the individual particles has a dispersed structure, and all particles are oriented more or less parallel to one another.

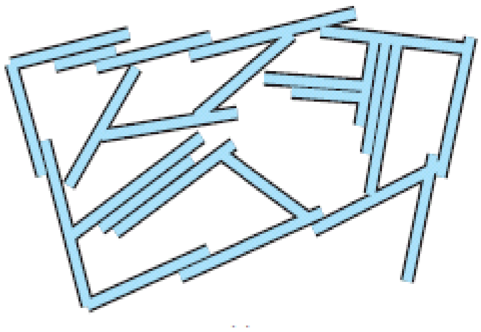


Dispersed structure

If the clay particles initially dispersed in water settle under the force of gravity and come close to one another during random motion in suspension, they might aggregate into visible flocs with edge-to-face contact. This aggregation is known as flocculation.



Nonsalt flocculation



Salt flocculation

- ❖ Clays that have flocculent structures are lightweight and possess high void ratios. Clay deposits formed in the sea are highly flocculent.
- ❖ Most of the sediment deposits formed from freshwater possess an intermediate structure between dispersed and flocculent.