Fundamentals of Geotechnical Engineering - II

Chapter 2

Simple Soil Properties

AAiT
Addis Ababa Institute of Technology
Addis Ababa University

Geotechnical Engineering Chair

School of Civil & Environmental Engineering

General Outline

- Introduction
- Phase Relationships
- Grain Size Distribution
- Soil Consistency

1. Introduction

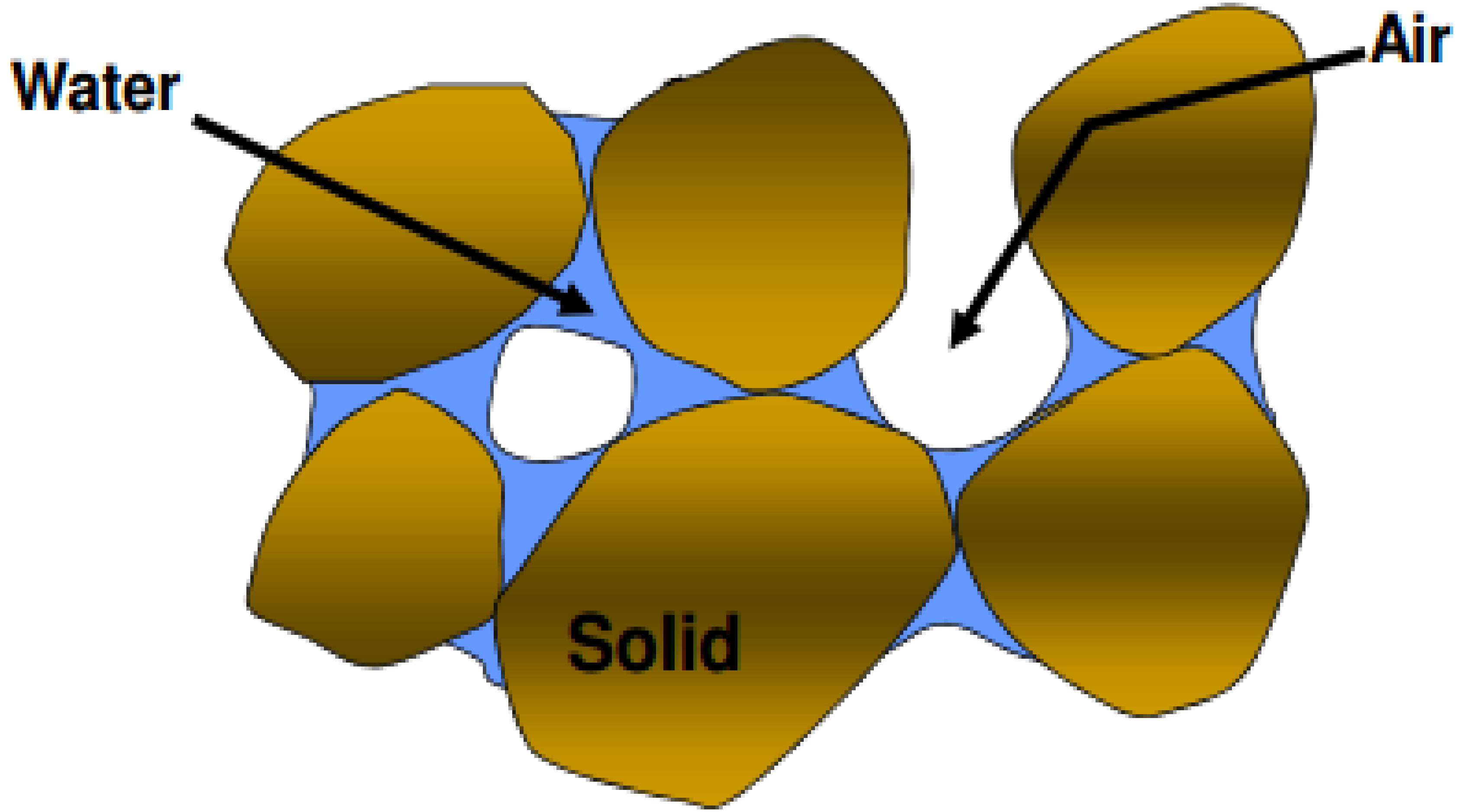
- Soil: a Particulate Material
- Idealized Phase Diagram

Introduction

Soil : a particulate material.

- A sample of soil is made up of countless particles of a variety of shapes and sizes.
- The particles are in contact with each other, and the arrangement of particles is often referred to as the ‘soil skeleton’.
- Spaces exist between the particles and are referred to as the ‘voids’.
- The voids may be filled with water or a mixture of water and air.

Introduction cntd

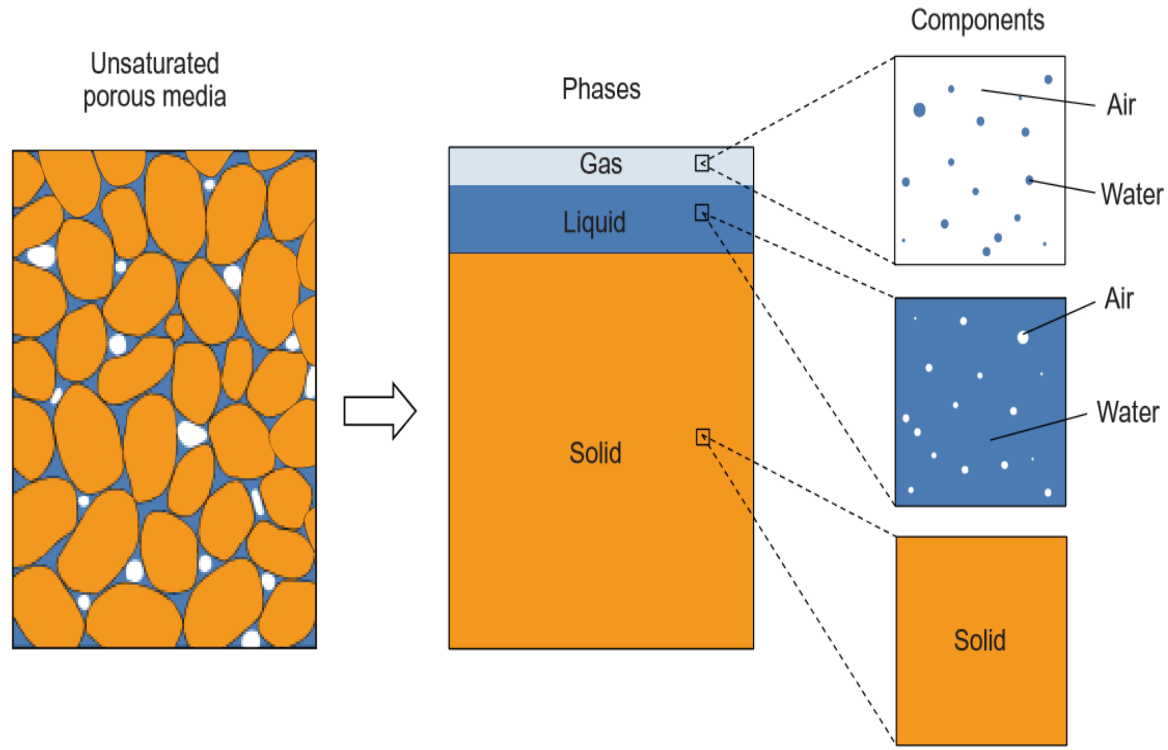


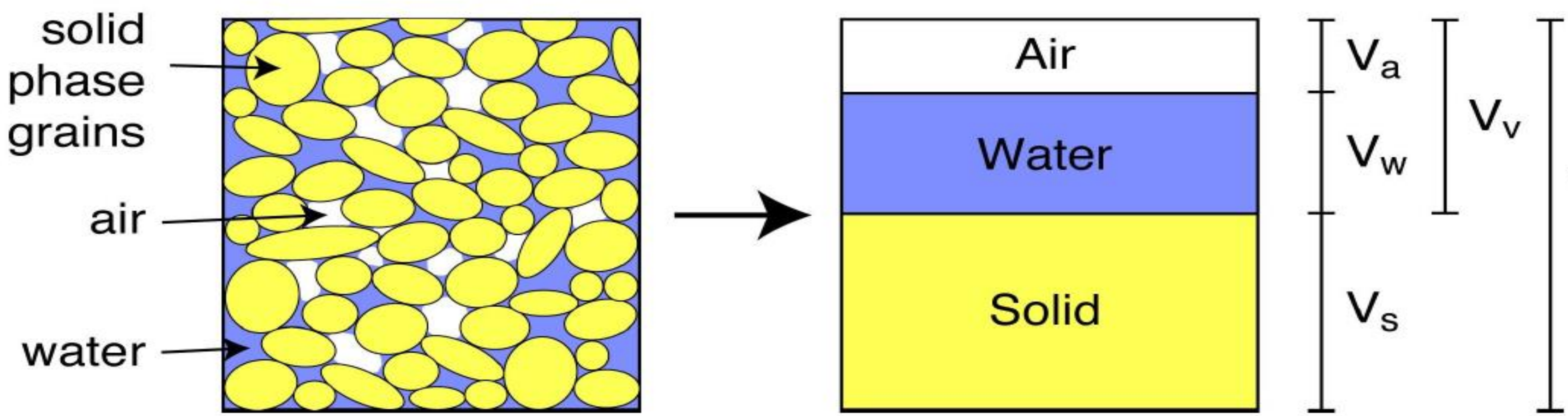
Introduction cntd

Soil : a particulate material

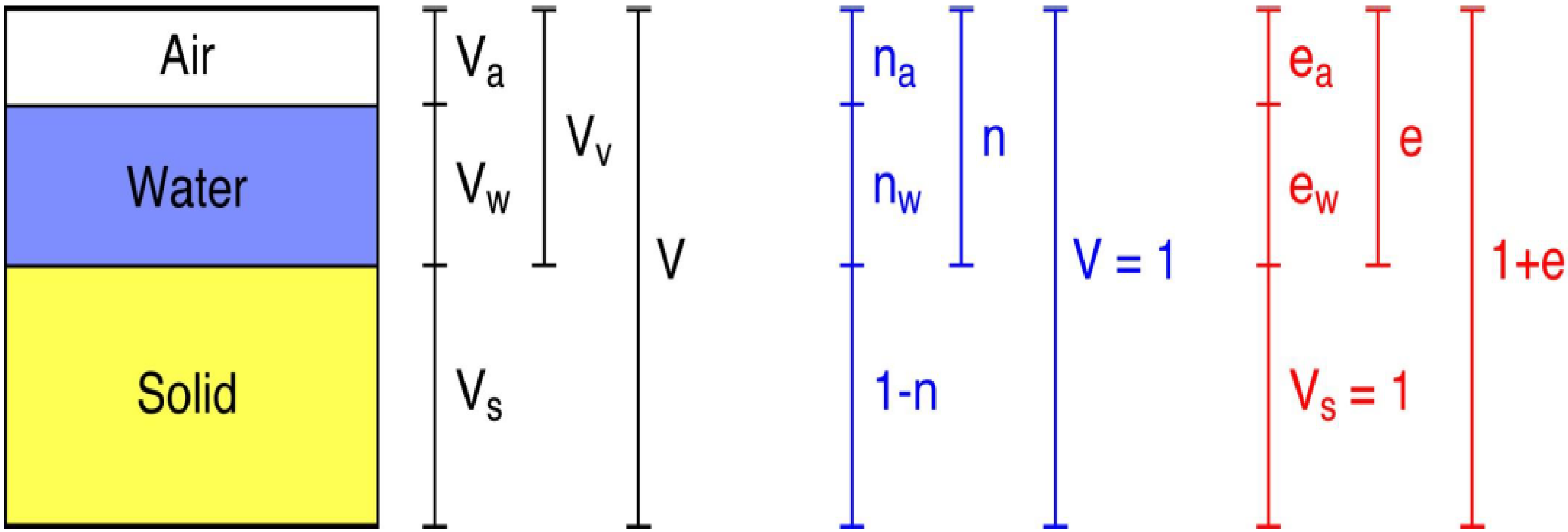
- The closeness of packing of the particles has a dominant influence on the mechanical behavior of a soil. The more densely packed the particles, the greater will be the stiffness and strength of the soil and the lower will be its permeability.
- In order to carry out calculations of ground displacement and stability, it is necessary to idealize the soil as a continuum with certain stiffness and strength properties.

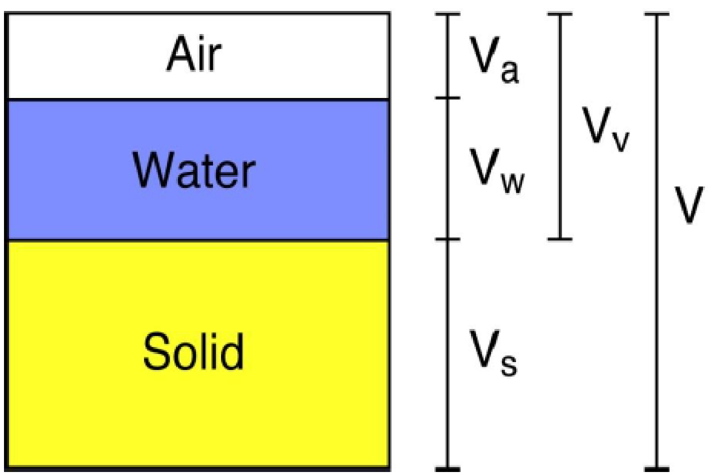
Introduction





Introduction cntd





Density	Mass	Weight
$\rho = 0$	$m_a = 0$	$W_a = 0$
$\rho = \rho_w$	$m_w = \rho_w V_w$	$W_w = \gamma_w V_w$
$\rho = \rho_s$	$m_s = \rho_s V_s$	$W_s = \gamma_s V_s$

2. Phase Relations

- Weight relations
- Volume relations
- Weight-volume relations
- Cross-parameter relations

Phase Relations

Weight/Mass Relationships

Gravimetric Water Content (ω) [%]: ratio of the mass of water, Mw, to the mass of soil solids, Ms.

Referred to simply as water content in many literatures.

$$\omega = \frac{Mw}{Ms} \times 100$$

Water Content Test – Oven Dry Method

Apparatus: Drying oven, dessiccator, balance, containers,

Procedure:

1. Clean the container, dry it and weigh it with the lid (W_1)
2. Take the required quantity of wet soil specimen in the container and weight it with the lid (W_2)
3. Place the container, with its lid removed, in the oven till its weight becomes constant. (Normally 24hours suffice)
4. When the soil has dried, remove the container from the oven, using tongs.
5. Measure the weight W_3 of the container with the lid and dry soil sample.

$$\omega = \frac{[W_2 - W_3]}{[W_3 - W_1]} \times 100\%$$

Exercise 2.2.1 – MOISTURE CONTENT

A sample of saturated clay was placed in a container and weighed. The weight was 6 N. The clay in its container was placed in an oven dry for 24 hours at 105°C. The weight reduced to a constant value of 5 N. The weight of the container is 1 N.

Determine the water content.

Phase Relations cntd

Volume Relationships

Porosity (n) [%]: ratio of the volume of voids, Vv, to the total volume, V.

$$\eta = \frac{Vv}{V} \times 100$$

Void Ratio (e) [-]: ratio of the volume of the voids, Vv, to the volume of the soil solids, Vs.

$$e = \frac{Vv}{Vs}$$

Volume Relationships

Degree of Saturation (S) [%]: percentage of the void space which contains water.

$$S = \frac{Vw}{Vv} \times 100$$

Volumetric Water Content (θw) [-]: ratio of the volume of water, Vw, to the total volume of the soil, V. Also referred to as the water porosity, nw.

$$\theta w = \frac{Vw}{V}$$

Phase Relations cntd

Percent Air Voids (n_a) [-]: ratio of the volume of air voids to the total volume of the soil mass.

$$n_a = \frac{V_a}{\mathrm{V}}$$

Air Content (a_c) [-]: ratio of the volume of air voids to the volume of voids.

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

Specific Volume (V') [-]: the volume of soil per unit volume of solids.

$$V' = \frac{V}{V_s}$$

Phase Relations cntd

Weight-Volume Relationships i.e. Soil Density

Total Density (ρ) [kg/m^3]: ratio of the total mass, M, to the total volume of the soil, V. Also referred to as the bulk density. (Current state density)

$$\rho = \frac{M}{V}$$

Dry Density (ρ_d) [kg/m^3]: ratio of the mass of the soil solids, Ms, to the total volume of the soil, V.

$$\rho\, d = \frac{Ms}{V}$$

Saturated Density (ρ_{sat}) [kg/m^3]: density of the soil when the voids are filled with water.

Phase Relations cntd

Submerged Density (ρ') [kg/m³]: effective density of the soil when it is submerged.

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

NB. Unit Weight: $\boldsymbol{\gamma = \rho g}$

Table: Typical values of unit weight for soils

Soil type	γ_{sat} **(kN/m³)**	γ_d **(kN/m³)**
Gravel	20–22	15–17
Sand	18–20	13–16
Silt	18–20	14–18
Clay	16–22	14–21

Exercise 2.2.2 – WEIGHT-VOLUME RELATIONS

A sample of clay is brought back from the field, extruded from the Shelby tube, and trimmed to the following dimensions: height=150 mm, diameter=75 mm. It weighs 13.2 N. The water content has been determined to be 25%.

Find following parameters for the clay.

a. Natural unit weight

b. Degree of saturation

c. Porosity

d. Void ratio

e. Dry unit weight

f. Saturated unit weight

Phase Relations cntd

Specific Gravity (G_s) [-]

- ratio of the weight of a given volume of a material to the weight of an equal volume of water.
- typically varies between 2.6 and 2.8 for soils

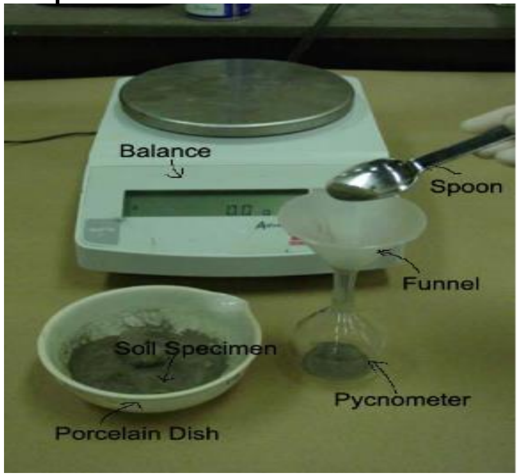
$$Specific\ Gravity = \frac{Unit\ weight\ of\ a\ Substance}{Unit\ weight\ of\ Water}$$

For soils, $G_s = \gamma_{soil\ solids}/\gamma_w$

Unit weight of water, $\gamma_w = 1.0\ g/cm^3 = 9.81\ kN/m^3$

Specific Gravity – PYCNOMETER METHOD

1. Measure empty clean and dry pycnometer, W_P
2. Measure pycnometer and 10gm soil, W_{PS}
3. Add 3/4th water and soak for 10min.
4. Apply partial vacuum for 10min.
5. Fill with water up to the mark.
6. Clean and measure, W_{PSW}
7. Fill empty pycnometer with water and measure, W_{PW}



$$Gs = \frac{W_{PS} - W_P}{(W_{PW} - W_P) - (W_{PSW} - W_{PS})}$$

Exercise 2.2.3 - PYCNOMETER

A pycnometer test was conducted on a soil. The data are as shown below. Calculate the specific gravity.

Mass of pycnometer	= 38.2 g
Mass of pycnometer and dry soil	= 64.3 g
Mass of pycnometer, dry soil, and water	= 154.8 g
Mass of pycnometer and water	= 138.5 g

Phase Relations cntd

Specific Gravity – GAS JAR METHOD

1. Place oven dried soil [S] (approximately 200 g for a fine soil and 400 g for a medium or coarse soil) into the gas jar [J] along with about 500 ml of distilled water [W] at room temperature.
2. Seal the jar with the bung and shaken, first by hand and then in the machine, for 20 to 30 minutes.
3. Remove the bung, top up the jar carefully to full capacity with further distilled water and slide the glass plate on top to seal the jar without trapping any air inside.
4. From various weighings that are made the specific gravity of the soil can be calculated:

$$Gs = \frac{S}{[(J+W)-(J+W+S)+S]}$$

Exercise 2.2.4 – GAS JAR

The mass of an empty gas jar, together with its glass cover plate, was 478.0 g. When completely filled with water and the cover plate fitted the mass was 1508.2 g. An oven dried sample of soil was inserted in the dry gas jar and the total mass, including the cover plate, was 676.6 g. Water was added to the soil and, after a suitable period of shaking, was topped up until the gas jar was brim full. The cover plate was fitted and the total mass was found to be 1632.6 g.

Determine the particle specific gravity of the soil.

Phase Relations cntd

Cross-Parameter Relations

Consider a fraction of the soil

where Vs=1

$$Mw = \rho w \times Vw$$

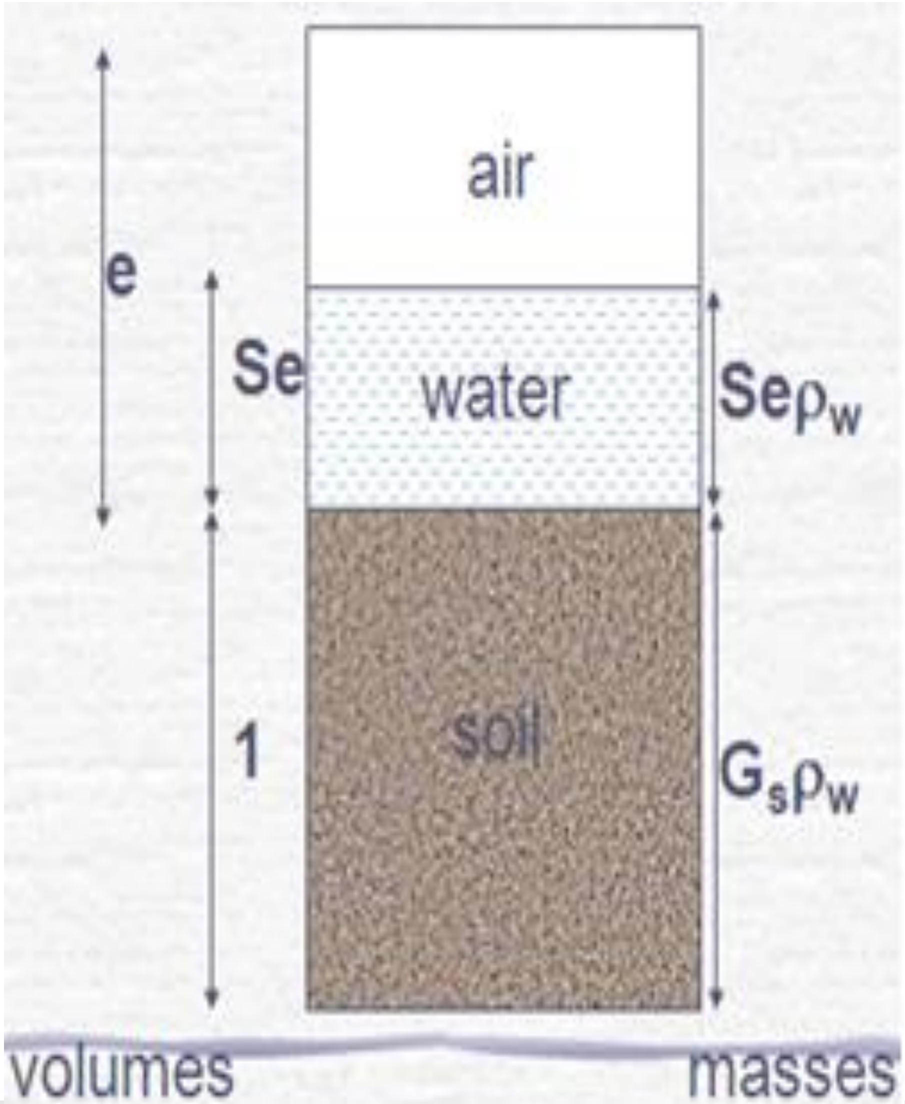
$$Vw = S \times e \times Vs$$

$$Mw = \rho w \times S \times e \times Vs$$

$$Mw = \omega \times Ms$$

$$Ms = Gs \times \rho w \times Vs$$

$$S \times e = \omega \times Gs$$



Cross-Parameter Relations

$$Vs = 1 \Rightarrow e = Vv$$

$$\eta = \frac{Vv}{V} = \frac{Vv}{Vs + Vv} = \frac{e}{1 + e}$$

$$\rho = \frac{M}{V} = \frac{Ms + Mw}{Vs + Vv} = \frac{Gs \times \rho w \times Vs \ + \ \omega \times Gs \times \rho w \times Vs}{Vs + e \times Vs}$$

$$= \frac{Gs(1 + \omega)}{1 + e} \times \rho w = \frac{Gs \ + \ S \times e}{1 + e} \times \rho w$$

$$\rho\ sat = \frac{Gs + e}{1 + e} \times \rho w; \qquad \rho\ d = \frac{Gs}{1 + e} \times \rho w$$

Phase Relations cntd

- $n = \frac{e}{1+e}$
- $e = \frac{n}{1-n}$
- $e = \frac{(\gamma_s - \gamma_d)}{\gamma_d}$
- $Se = \omega G_s$

- $\gamma_d = \frac{\gamma}{1+\omega}$
- $\gamma = \gamma_w(G_s(1-n) + Sn)$
- $\gamma = \frac{\gamma_w(G_s + Se)}{(1+e)}$
- $\gamma_d = \gamma_w G_s(1-n)$

Exercise 2.2.5 – CROSS PARAMETERS

Show that $\gamma_d = \frac{\gamma_s}{(1+e)}$ by the use of the idealized phase diagram.

Also derive the expression $\gamma_d = \frac{\gamma}{1+\omega}$

Relative Density (Dr) [-]

- an index that indicates the degree of packing between the loosest and densest possible state of coarse-grained soils as determined by experiments:

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

where e_{max} is the maximum void ratio (loosest condition), e_{min} is the minimum void ratio (densest condition), e is the current void ratio.

Phase Relations cntd

The maximum void ratio is obtained by pouring dry sand into a mold of volume (*V*) 2830cm^3 using a funnel. The sand that fills the mold is weighed. If the weight of the sand is *W*, then $e_{max} = G_s\gamma_w(V/W) - 1$.

One method of determining the minimum void ratio is by vibrating the sand with a weight imposing a vertical stress of 14kPa on top of the sand. Vibration occurs for 8 minutes at a frequency of 3600Hz and amplitude of 0.33mm. From the weight of the sand (*W*1) and the volume (*V*1) occupied by it after vibration, we can calculate the minimum void ratio using $e_{min} = G_s\gamma_w(V_1/W_1) - 1$.

Phase Relations cntd

- The maximum void ratio is a basic soil property, but the minimum void ratio is not—it depends on the method used to obtain it.
- In practice, geoengineers have correlated relative density with various parameters for coarse-grained soils (essentially sand).

D_r (%)	Porosity, n (%)	Description
0–20	100–80	Very loose
20–40	80–60	Loose
40–70	60–30	Medium dense or firm
70–85	30–15	Dense
85–100	<15	Very dense

Density Index (I_d)

- is a similar (not identical) measure to relative density.

$$I_d = \frac{\gamma_d - (\gamma_d)_{min}}{(\gamma_d)_{max} - (\gamma_d)_{min}}$$

$$D_r = I_d \left\{ \frac{(\gamma_d)_{max}}{\gamma_d} \right\}$$

NB. Most correlations developed are often weak (low coefficient of regression). However, they serve as guidance for preliminary assessment of earthworks, foundations and vibrations of sand.

Exercise 2.2.6 – RELATIVE DENSITY

Calculate the relative density and classify the compactness of a dry sandy soil with a weight of 50 N, a total volume of 3000 cm^3 and a specific gravity of 2.7. The void ratios of the material in its densest and loosest conditions are 0.25 and 0.75 respectively.

Swell Factor (SF) [Free Swell]

- ratio of the volume of excavated material to the volume of insitu materal (sometimes called burrow pit material or bank material).

$$SF = \frac{Volume\ of\ excavated\ material}{Volume\ of\ in\ situ\ material} * 100\%$$

Clay minerals	Free swell (%)
Calcium montmorillonite (Ca-smectite)	45–145
Sodium montmorillonite (Na-smectite)	1400–1600
Illite	15–120
Kaolinite	5–60

Exercise2.2.7 - APPLICATION OF PHASE RELATIONSHIPS TO PRACTICAL PROBLEMS

An embankment for a highway is to be constructed from a soil compacted to a dry unit weight of 18 kN/m^3. The clay has to be trucked to the site from a burrow pit. The bulk unit weight of the soil in the burrow pit is 17 kN/m^3 and its natural water content is 5%.

Calculate the volume of clay from the burrow pit required for 1 cubic meter of embankment.

The swell factor is 1.2 (20% free swell). Assume G_s = 2.7.

Exercise2.2.8 - APPLICATION OF PHASE RELATIONSHIPS TO PRACTICAL PROBLEMS

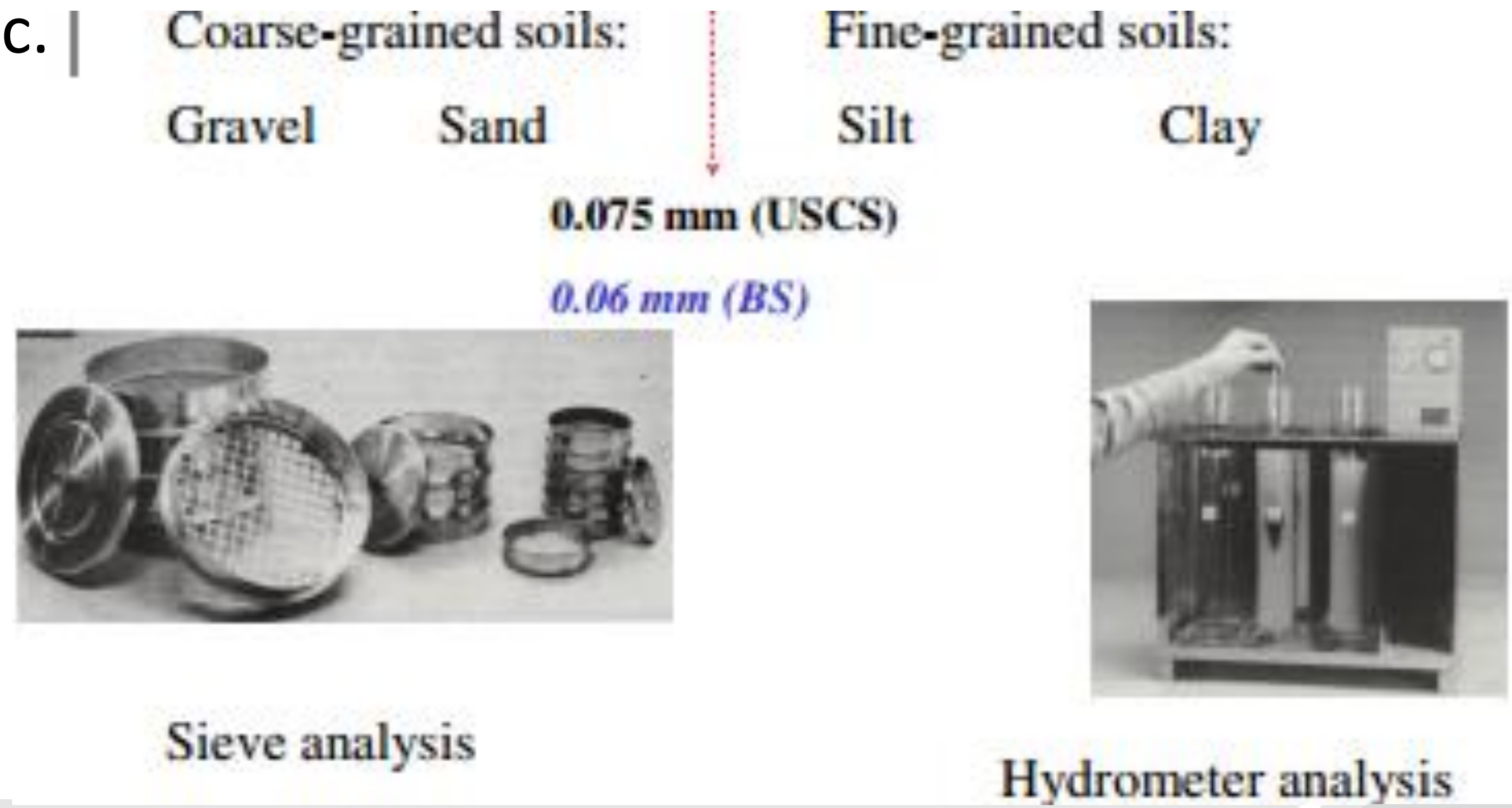
If the burrow soil in previous exercise were to be compacted to attain a dry unit weight of 18 kN/m^3 at a water content of 7%, determine the amount of water required per cubic meter of embankment, assuming no loss of water during transportation.

3. Grain Size Distribution

- Grain Size Distribution Analysis
    - Sieve Analysis
    - Hydrometer Analysis
    - Combined Analysis
- Grain Size Distribution Curves

Grain Size Distribution

Grain Size Distribution information can be of value in providing initial rough estimates of a soil's engineering properties such as permeability, strength, expansivity, etc.



Grain Size Distribution cntd

Sieve Analysis (Mechanical Analysis)

- The distribution of particle sizes or average grain diameter of coarse-grained soils—gravels and sands— is obtained by screening a known weight of the soil through a stack of sieves of progressively finer mesh size.
- The determination of the size range of particles present in a soil, expressed as a percentage of the total dry weight.

-#10 sieve has 10 apertures per linear inch

Grain Size Distribution cntd

- Each sieve is identified by either a number that corresponds to the number of square holes per linear inch of mesh or the size of the opening. E.g. --#10 sieve has 10 apertures per linear inch
- Large sieve (mesh) openings (25.4 mm to 6.35 mm) are designated by the sieve opening size, while smaller sieve sizes are designated by numbers.
- The particle diameter in the screening process, often called sieve analysis, is the maximum dimension of a particle that will pass through the square hole of a particular mesh.

Grain Size Distribution cntd

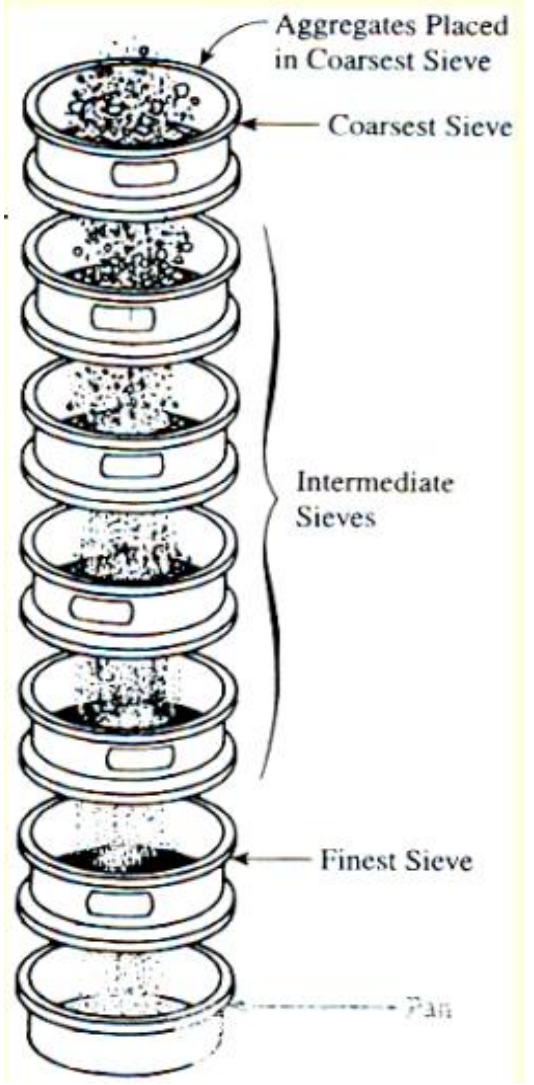
ASTM Standard Sieves

Sieve Identification	Opening Size (in)	Opening Size (mm)
3 inch	3.00	76.2
2 inch	2.00	50.8
1½ inch	1.50	38.1
1 inch	1.00	25.4
3/4 inch	0.75	19.0
3/8 inch	0.375	9.52
#4	0.187	4.75
#8	0.0929	2.36
#10	0.0787	2.00

Sieve Identification	Opening Size (in)	Opening Size (mm)
#16	0.0465	1.18
#20	0.0335	0.850
#30	0.0236	0.600
#40	0.0167	0.425
#50	0.0118	0.300
#60	0.00984	0.250
#100	0.00591	0.150
#140	0.00417	0.106
#200	0.00295	0.075

Grain Size Distribution cntd

- A known weight of dry soil is placed on the largest sieve (the top sieve) & the nest of sieves is then placed on a vibrator, called a sieve shaker, and shaken.
- The nest of sieves is dismantled, one sieve at a time.
- The soil retained on each sieve is weighed, and the percentage of soil retained on each sieve is calculated.



Grain Size Distribution cntd

- The results are plotted on a graph of percent of particles ***finer*** than a given sieve size (not the percent retained) as the ordinate versus the logarithm of the particle sizes.
- The resulting plot is called a particle size distribution curve or, simply, the gradation curve.

Let *Wi* be the weight of soil retained on the *i*th sieve from the top of the nest of sieves and *W* be the total soil weight.

$$\%\, retained\ on\ i^{th}\ sieve = \frac{W_i}{W} * 100\%$$

$$\%\, finer\ than\ the\ i^{th}\ sieve = 100 - \sum_{i=1}^{i} (\%\, retained\ on\ i^{th}\ sieve)$$

Grain Size Distribution cntd

EXERCISE 2.3.1 – SIEVE ANALYSIS

A sieve analysis test was conducted on 650 grams of soil. The results are as follows. Plot grading curve.

Sieve no.	(3/8")	4	10	20	40	100	200	Pan
Opening (mm)	9.53	4.75	2	0.85	0.425	0.15	0.075	
Mass retained (g)	0	53	76	73	142	85	120.5	99.8

Grain Size Distribution cntd

Hydrometer Analysis

- The screening process (sieve analysis) cannot be used for fine-grained soils—silts and clays—because of their extremely small size.
- The common laboratory method used to determine the size distribution of fi ne-grained soils is a hydrometer test.
- Based on the process of sedimentation of soil particles in water by gravity.
- Separation of particles of various sizes by their velocity.

Grain Size Distribution cntd

- The hydrometer test involves mixing a small amount of soil into a suspension and observing how the suspension settles in time.
- Larger particles will settle quickly, followed by smaller particles.
- Velocity depends on specific gravity, weight, diameter, density and viscosity.
- When the hydrometer is lowered into the suspension, it will sink into the suspension until the buoyancy force is sufficient to balance the weight of the hydrometer.

Grain Size Distribution cntd

- A small quantity of a dry, fine-grained soil (approximately 50 grams) is thoroughly mixed with distilled water a dispersing agent to form a paste.
- The paste is placed in a 1-liter glass cylinder, and distilled water is added to bring the level to the 1-liter mark.
- The glass cylinder is then repeatedly shaken and inverted before being placed in a constant-temperature bath.
- A hydrometer is placed in the glass cylinder and a clock is simultaneously started.

Grain Size Distribution cntd

- The hydrometer is inserted in the suspension and the first reading is taken after ½ min. of the commencement of the sedimentation.
- Further reading are taken after 1, 2, and 4 min of the commencement of the sedimentation.
- The hydrometer is then removed from the jar and rinsed and floated in a comparison cylinder filled with distilled water with the dispersion agent added to the same concentration as in the soil suspension.
- Further reading are taken after 8, 15, 30 min and 1, 2, 4, 8 and 24 hrs from the beginning of sedimentation.

Grain Size Distribution cntd

- The diameter D (cm) of the particle at time t_D (seconds) is calculated from Stokes's law as

$$D = \sqrt{\frac{18\mu Z_r}{(G_s - 1)\rho_w g t_D}}$$

Where μ is the viscosity of water [0.01 gram/(cm.s) at 20^{o}C], z_r is the depth (cm), ρ_w is the density of water (1g/cm^3), g is the acceleration due to gravity (981 cm/s^2), and G_s is the specific gravity of the soil particles.

NB. The equation applies to early readings taken between ¼ and 2 minutes. For further readings, emersion correction is applied to the equation.

Grain Size Distribution cntd

- In the application of Stokes's law, the particles are assumed to be free-falling spheres with no collision. But the mineral particles of clays are platelike, and collision of particles during sedimentation is unavoidable.
- Also, Stokes's law is valid only for ***laminar flow*** with Reynolds number ($R_e = \frac{vD\gamma_w}{\mu g}$, where v is velocity, D is the diameter of the particle, γ_w is the unit weight of water, μ is the dynamic viscosity of water at 20°C, and g is the acceleration due to gravity) smaller than 1.

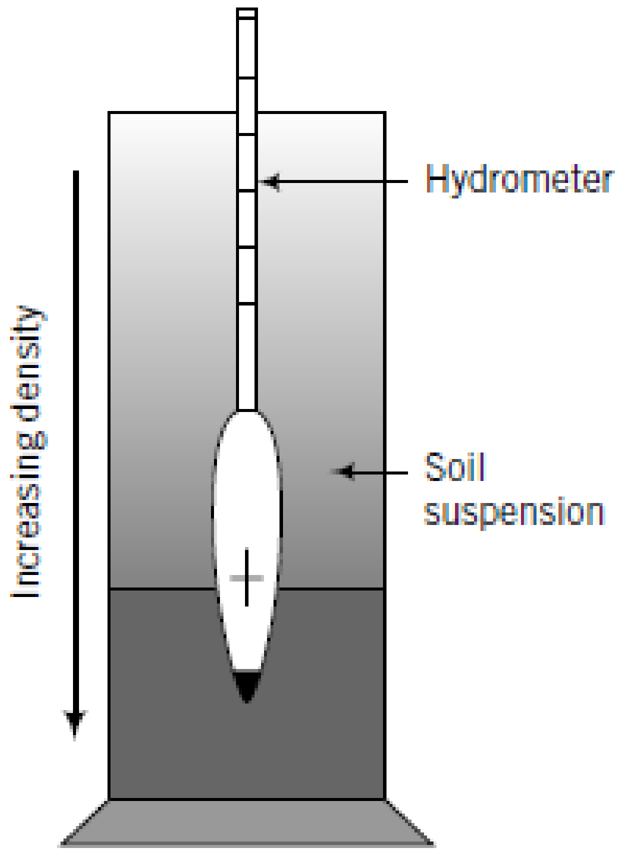
Grain Size Distribution cntd

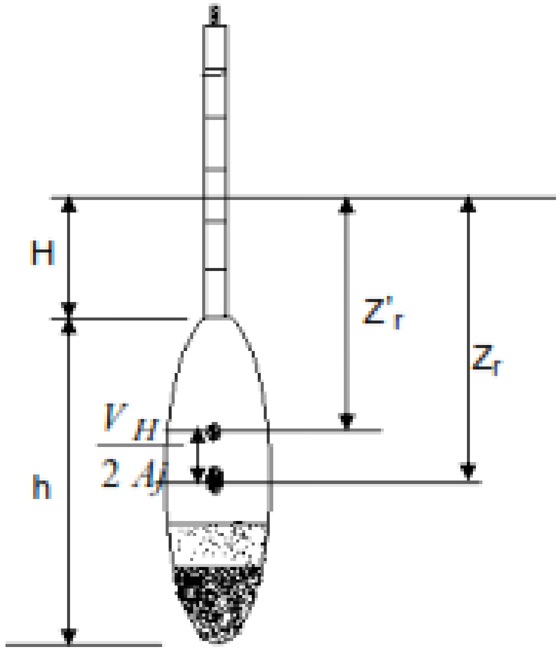
EXERCISE 2.3.2 – HYDROMETER ANALYSIS

After a time of 1 minute in a hydrometer test, the effective depth was 0.8cm. The average temperature measured was 20° C and the specific gravity of the soil particles was 2.7. Calculate the diameter of the particles using Stokes's law. Are these silt or clay particles?

Grain Size Distribution cntd

- The hydrometer projecting above the suspension is a function of the density, so it is possible to calibrate the hydrometer to read density of the suspension at different time.



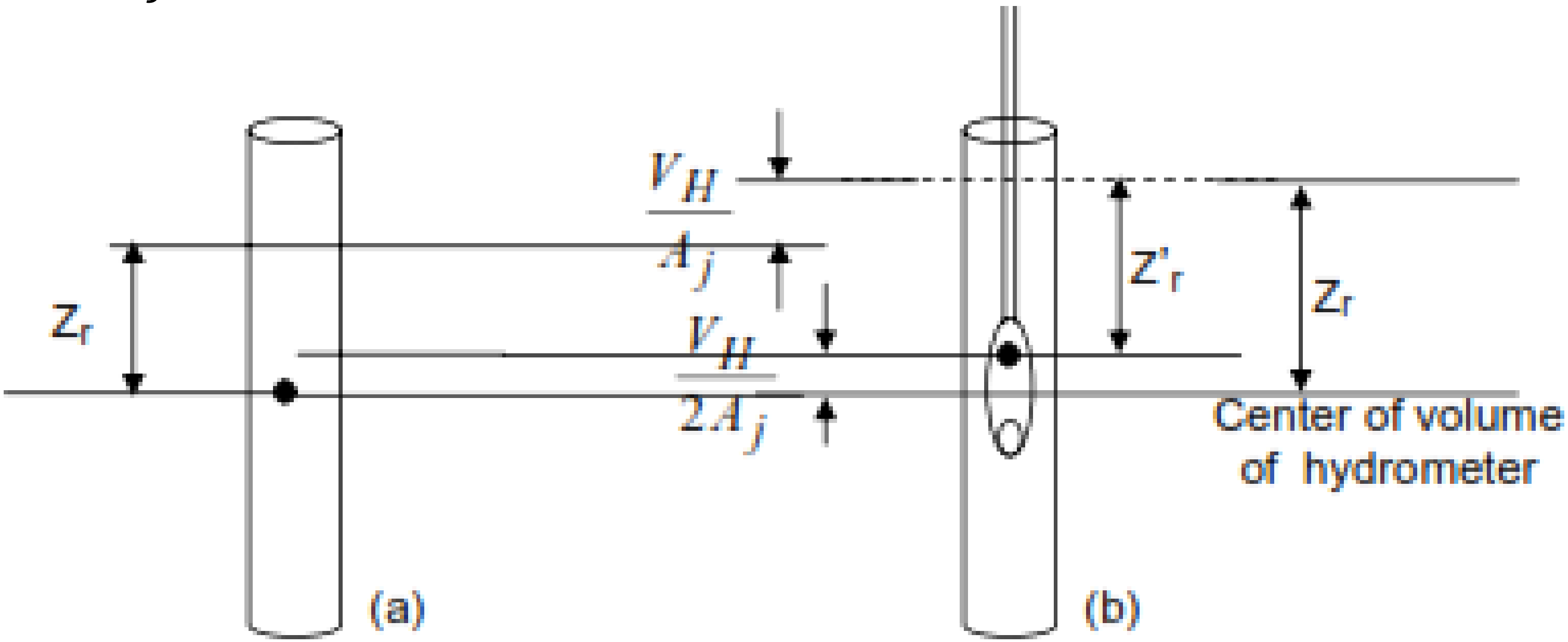


$V_H = volume\ of\ hydrometer$

$A_j = crossectional\ area\ of\ jar$

Grain Size Distribution cntd

When the hydrometer is placed in the jar, it displaces its own volume. Thus the surface of the suspension rises by V_H / A_j



a) Before the immersion of hydrometer b) After the immersion of hydrometer

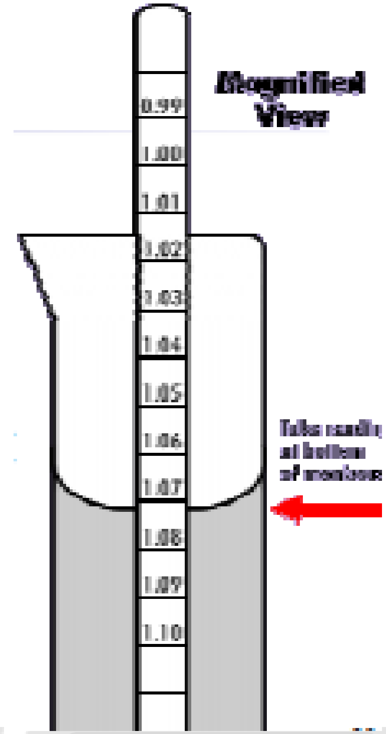
Grain Size Distribution cntd

- Hydrometer measures the specific gravity at the center of the bulb which means the liquid now at the center of the bulb was previously at lower level (i.e. before immersion of hydrometer).
- Since the displacement below the center of the bulb is due to half its volume, the liquid now at the center must be lowered by $V_H/2A_j$
- Thus actual distance of settlement is $\boldsymbol{z_r' = z_r - \frac{V_H}{2A_j}}$

$$\boldsymbol{D = \sqrt{\frac{18\mu(z_r - \frac{V_H}{2A_j})}{(G_s - 1)\rho_w g t_D}}}$$

Grain Size Distribution cntd

- The calibration of the hydrometer is affected by temperature and the specific gravity of the suspended solids.
- A correction factor must be applied to hydrometer readings based on the test temperatures.
  - Meniscus correction (+)
  - Temperature correction (±)
  - Dispersing agent correction (–)



Grain Size Distribution cntd

Percentage Finer

Mass of solid in suspension = $W\ (g)$

Mass of solids per unit volume of suspension = $W/V\ \ (g/cm^3)$

Volume of solids per unit volume of suspension = $\frac{W/V}{\gamma_s} = \frac{W}{G_s V \gamma_w}\ \ (cm^3)$

Volume of water per unit volume of suspension = $1 - \frac{W}{G_s V \gamma_w}\ \ (cm^3)$

Mass of water per unit volume of suspension =$\gamma_w \left(1 - \frac{W}{G_s V \gamma_w}\right) = \gamma_w - \frac{W}{G_s V}$ (g/cm^3)

Density of suspension, $\gamma_i = \frac{W}{V} + \left(\gamma_w - \frac{W}{G_s V}\right) (g/cm^3)$

The percentage of particles N smaller than D

$$= \frac{weight\ of\ solids\ per\ cm^3\ at\ depth\ z_r\ after\ time\ t}{weight\ of\ solids\ per\ cm^3\ in\ the\ original\ suspension} * 100\%$$

Grain Size Distribution cntd

Weight of solid finer than D per unit volume of suspension after time t $= \frac{NW}{V}$

Weight of water per unit volume $= \gamma_w - \frac{NW}{G_s V}$

Unit weight, $\gamma = \frac{NW}{V} + \gamma_w - \frac{NW}{G_s V}$

$$\frac{NW}{V} - \frac{NW}{G_s V} = \gamma - \gamma_w$$

$$G_s NW - NW = G_s \mathrm{V}(\gamma - \gamma_w)$$
$$NW(G_s - 1) = G_s \mathrm{V}(\gamma - \gamma_w)$$

Percent finer than D, or $N = \frac{V}{W}\frac{G_s}{(G_s-1)}(\gamma - \gamma_w) = \frac{G_s V \gamma_c}{W(G_s-1)}(r - r_w)$

where

$\gamma_c = unit\ weight\ of\ water\ at\ temperature\ of\ hydrometer\ calibration$ (usually 20°C)
$r = hydrometer\ reading\ in\ suspension$
$r_w = hydrometer\ reading\ in\ water\ at\ the\ same\ temperature\ as\ suspension$

EXERCISE 2.3.3 – HYDROMETER ANALYSIS

In a hydrometer analysis, the following observations were taken: t= 4 minutes, r=1.015.

The weight of the solids used in suspension of 1000 cm^3 was 0.5N. Assume Gs=2.7

Calculate the coordinates of the point on the grain size plot. Other particulars of the hydrometer and the jar are as follows.

$$V_H = 50\ cm^3\ , \mu = 10 * 10^{-8}\ N\ sec/cm^2\ ,$$
$$h = 20\ cm, H = 2\ cm, A_j = 50\ cm^2$$

Grain Size Distribution cntd

Combined Analysis

1. Calculate the percent passing the No. 200 sieve. (This should be equal to the percent finer for the soil retained on No. 200 sieve from the Sieve Analysis)

2. The modified percent finer = percent finer for hydrometer method x percent passing No. 200 sieve from Step 1.

3. The total modified percent finer for samples retained on No. 200 sieve and above would be the same as calculated in sieve analysis; for samples passing No. 200 sieve, the same as calculated in Step 2.

$$N' = \frac{NW}{W_s}$$

$$W = total\ weight\ of\ dry\ soil\ passing\ sieve\ no. 200$$
$$W_s = total\ weight\ of\ dry\ soil\ used\ in\ the\ sieve\ analysis$$

Grain Size Distribution cntd

EXERCISE 2.3.4 – COMBINED ANALYSIS

The soil passing the No. 200 sieve in Example 2.3.1 was used to conduct a hydrometer test. The results are shown in the table below. Plot the grading curve.

Time (min)	Hydrometer reading (gram/liter)	Temperature (^oC)	Corrected distance of fall (cm)
1	40.0	22.5	8.90
2	34.0	22.5	9.21
3	32.0	22.0	9.96
4	30.0	22.0	10.29
8	27.0	22.0	10.96
15	25.0	21.5	11.17
30	23.0	21.5	11.45
60	21.0	21.5	11.96
240	17.0	20.0	12.45
900	14.0	19.0	13.10

Grain Size Distribution cntd

Grainsize Distribution Curves

- Help us "feel" the soil texture and used for the soil classification.
- Used to define the grading specification of a drainage filter (clogging)
- Used as a criterion for selecting fill materials of embankments, earth-dams, road sub-base materials, and concrete aggregates.
- Used to estimate the results of grouting and chemical injection, and dynamic compaction.
- More important to coarse-grained soils.

Grain Size Distribution cntd

- Shape of the curve indicates the nature of the soil tested.
  - Uniformly graded or poorly graded
  - Well graded
  - Gap graded

- In order to determine whether a material is uniformly graded or well graded two coefficients are used.
  - Uniformity coefficient, Cu
  - Coefficient of gradation(curvature or concavity), Cc

Grain Size Distribution cntd

1. Uniformity coefficient, Cu

$$C_u = D_{60}/D_{10}$$

- Cu < 4 - contains particles of uniform size, poorly graded
- Cu > 4 -contains wider assortment of particles, well graded

2. Coefficient of gradation, Cc

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

- Cc is used to diagnose gap graded
- It Cc ≠ 1-3, gap graded
- Also if sudden change is slope is observed in the curve

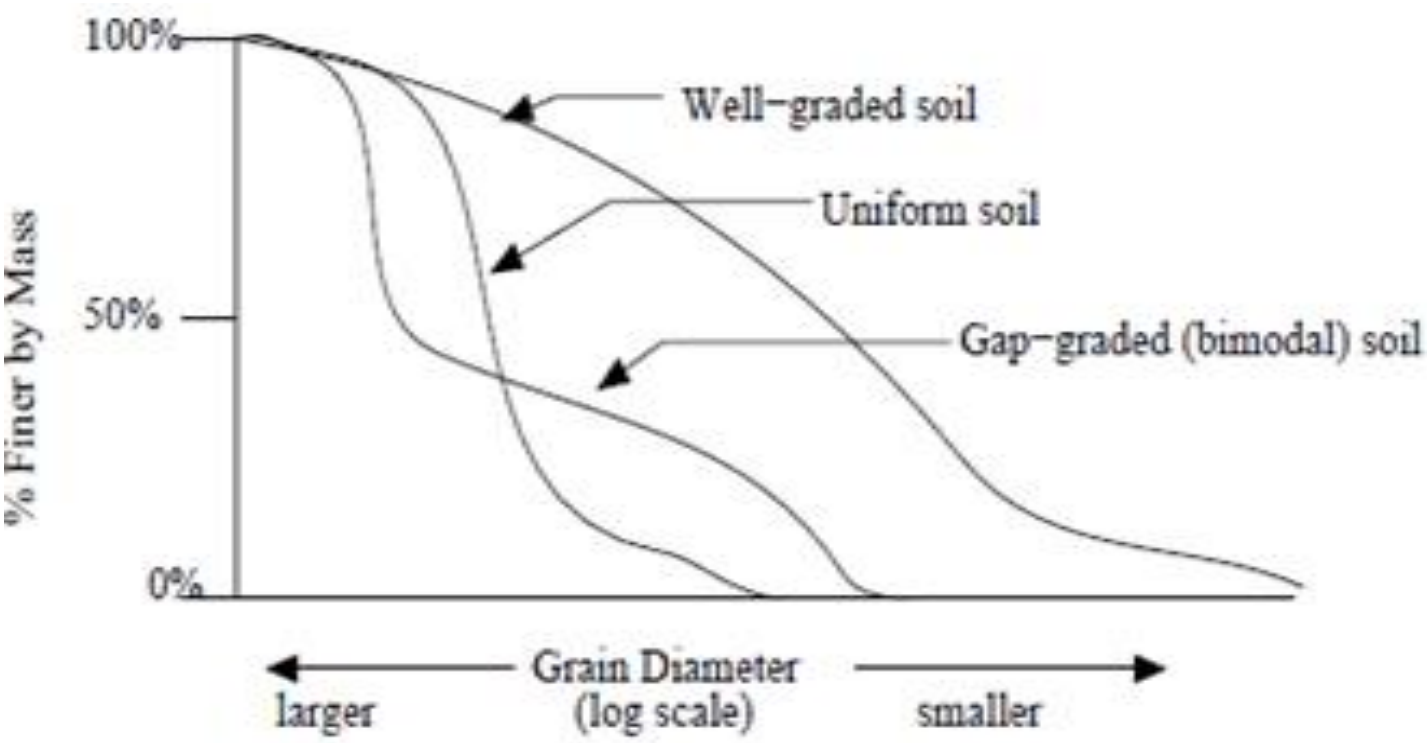
D_{60} , $D_{30,}$ D_{10}= diameter of the soil particle for which 60%, 30%, 10% (respectively) of the particles are finer

Grain Size Distribution cntd

Poorly-grade soils: C_u<4 & steep gradation curve

Well-graded soils: C_u>4, 1<C_c<3 & flat gradation curve

Gap-graded soils: C_c<1 or C_c>3 & one or more humps



Grain Size Distribution cntd

EXERCISE 2.3.5 – INTERPRETATION OF GSD CURVES

Based on the shape of the GSD curve produced in EXERCISE 2.3.4, state whether the soil is well, poorly or gap graded.

Also determine the effective size, average particle diameter. Calculate the uniformity coefficient and coefficient of curvature and state whether the soil is well, poorly or gap graded.

4. Soil Consistency

- Atterberg Limits
  - Liquid Limit
  - Plastic Limit
  - Shrinkage Limit
- Indices

Soil Consistency

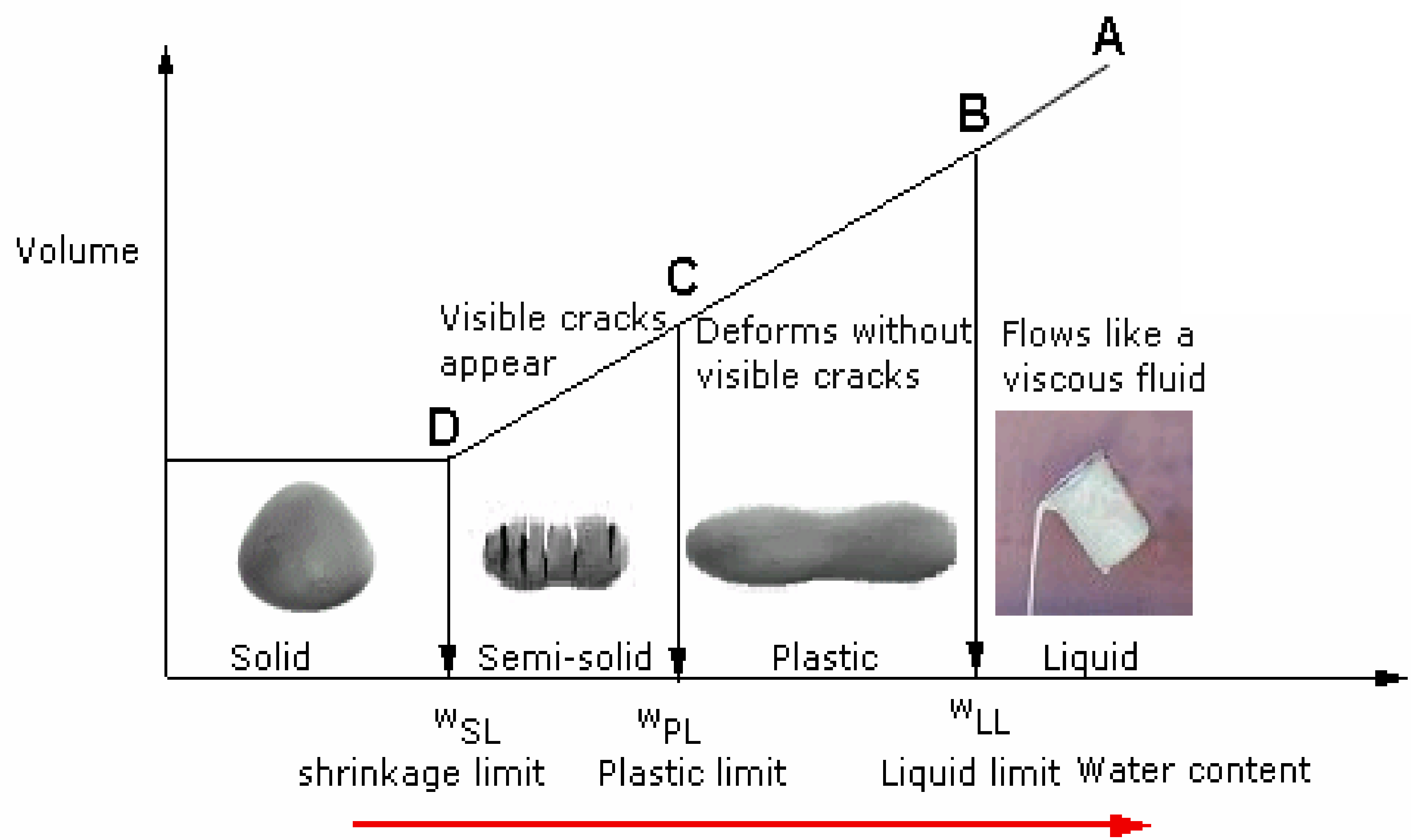
Soil Consistency

- defined as the relative ease with which a soil can be deformed. (The terms of soft, firm, or hard are used.)
- provides a means of describing the degree and kind of cohesion and adhesion between the soil particles as related to the resistance of the soil to deform or rupture.
- Consistency largely depends on soil minerals and the water content.

Soil Consistency cntd

- Physical properties of fine-grained soils greatly differ at different water contents.
- The presence of water in fine-grained soil can significantly affect associated engineering behavior.
- Depending on the moisture content, the behavior of soil can be divided into four basic states,
  - Solid
  - Semi-solid
  - Plastic
  - Liquid

Soil Consistency cntd



Soil Consistency cntd

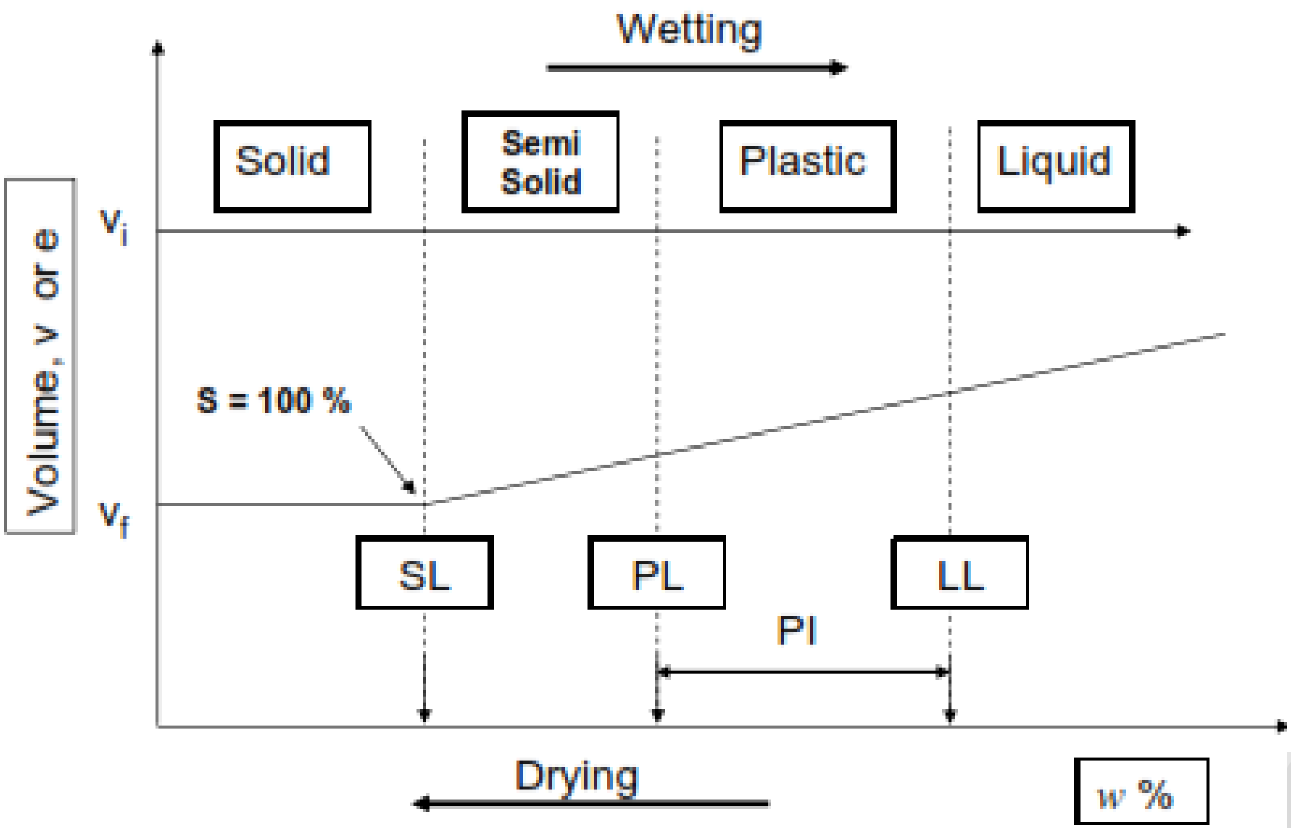
Atterberg Limits

Atterberg limits (consistency limits) are the moisture contents at which soil passes from one state to the next.

- Liquid Limit (LL) is defined as the moisture content at which soil begins to behave as a liquid material and begins to flow.
- Plastic Limit (PL) is defined as the moisture content at which soil begins to behave as a plastic material.
- Shrinkage Limit (SL) is defined as the moisture content at which no further volume change occurs with further reduction in moisture content.

Soil Consistency cntd

Shrinkage limit represents the amount of water required to fully saturate the soil (100% saturation) and it is useful for the determination of the swelling and shrinkage capacity of soils.



Soil Consistency cntd

Liquid Limit

- Moisture content at the point of transition from plastic to liquid state.
- Minimum moisture content at which the soil will flow under its own weight.

- The limits are determined on a soil sample passing sieve No. 40 (0.425mm)
- Liquid Limit tests
  - Casagrande Method
  - Cone Penetrometer Method

Soil Consistency cntd

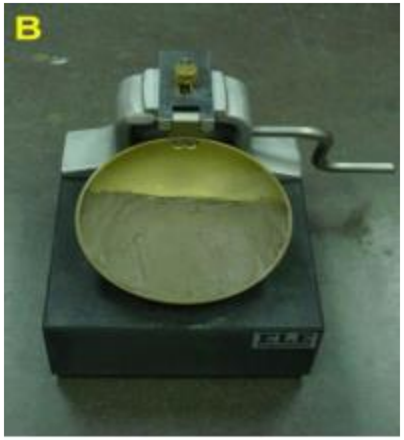
Liquid Limit Test (Casagrande Cup Method)

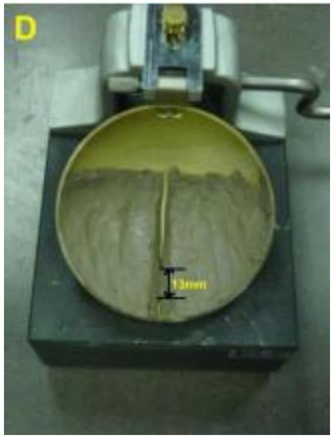
Procedure

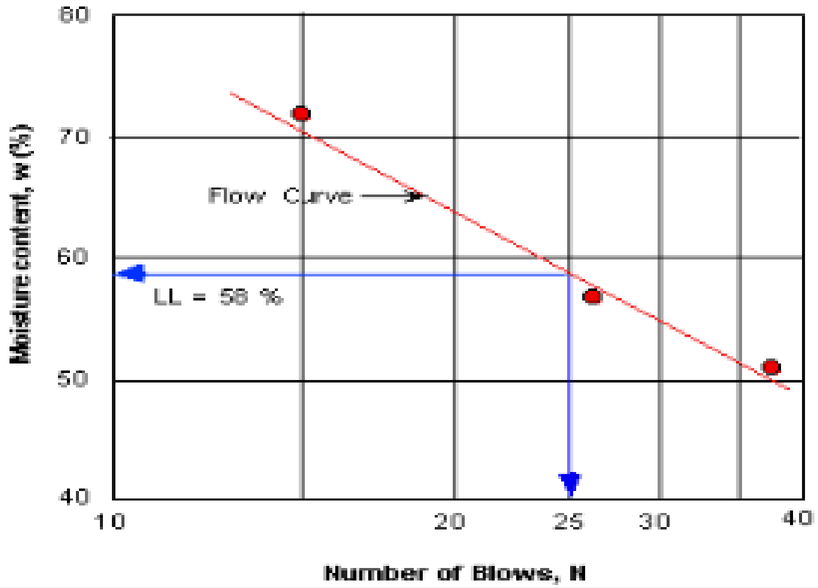
1. Take around 150g of dry soil passing No. 40 sieve.
2. Add some water and mix thoroughly.
3. Place a small sample of soil in the LL device
4. Cut a groove (2mm at the base)
5. Run the device, count the number of blows, N
6. Stop when the groove in the soil close through a distance of 12mm.
7. Take a sample and find the moisture content.
8. Run the test 3 times for N ≈10-20, N ≈ 20-30, N ≈ 35-45
9. Plot number of blows Vs moisture content (flow curve) and determine the LL (moisture content at 25 blows).

Soil Consistency cntd

Liquid Limit Test (Casagrande Method)







$$\omega = -I_f \log N + C$$

ω = Water content

I_f = Slope of the flow curve, termed as flow index

N = Number of blows

C = a constant

EXERCISE 2.4.1 - LIQUID LIMIT

The following data were recorded in a liquid limit test using the Casagrande apparatus.

Number of blows	Mass of can (g)	Mass of wet soil + can (g)	Mass of dry soil + can (g)
8	11.80	36.05	29.18
16	13.20	34.15	28.60
27	14.10	36.95	31.16
40	12.09	33.29	28.11

Determine the liquid limit of the soil.

Soil Consistency cntd

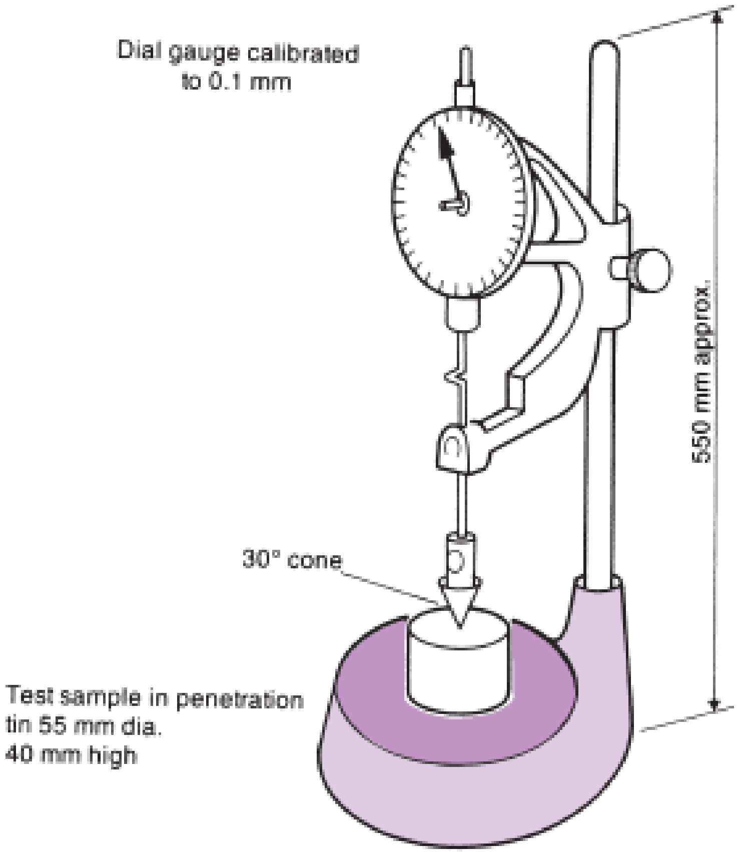
Liquid Limit Test (Cone penetrometer method)

- The soil to be tested is air dried and thoroughly mixed.
- At least 200 g of the soil is sieved through a 425 µm sieve and placed on a glass plate.
- The soil is then mixed with distilled water into a paste.
- A metal cup, approximately 55 mm in diameter and 40 mm deep, is filled with the paste and the surface struck off level.
- The cone, of mass 80 g, is next placed at the centre of the smoothed soil surface and level with it.
- The cone is released so that it penetrates into the soil and the amount of penetration, over a time period of 5 seconds, is measured.

Soil Consistency cntd

Liquid Limit Test (Cone penetrometer method)

- The test is now repeated by lifting the cone clear, cleaning it and filling up the depression in the surface of the soil by adding a little more of the wet soil.
- If the difference between the two measured penetrations is less than 0.5 mm then the tests are considered valid.
- The average penetration is noted and a water content determination is carried out on the soil tested.



Cone penetrometer

Liquid Limit Test (Cone penetrometer method)

- The procedure is repeated at least four times with increasing water contents.
- The amount of water used throughout should be such that the penetrations obtained lie within a range of 15 to 25 mm.
- To obtain the liquid limit the variation of cone penetration is plotted against water content and the best straight line is drawn through the experimental points.
- The liquid limit is taken to be the water content corresponding to a cone penetration of 20 mm (expressed as a whole number).

EXERCISE 2.4.2 - LIQUID LIMIT

A BS cone penetrometer test was carried out on a sample of clay with the following results:

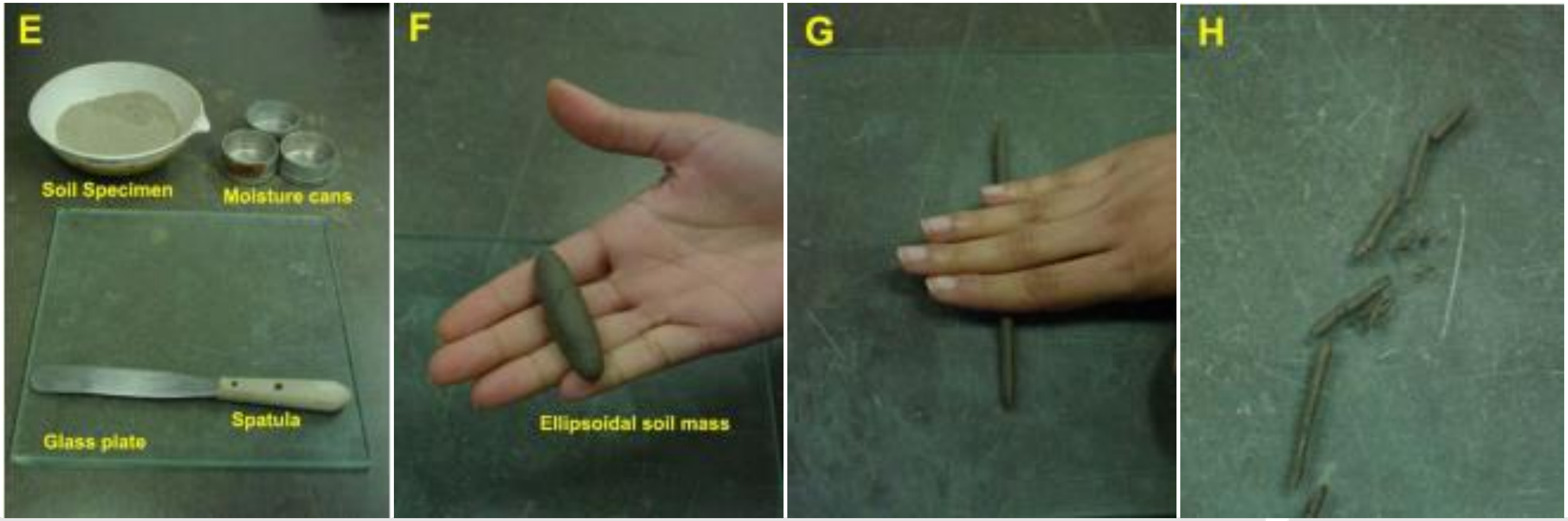
Cone penetration (mm)	16.1	17.6	19.3	21.3	22.6
Water content (%)	50.0	52.1	54.1	57.0	58.2

Determine the liquid limit of the soil.

Soil Consistency cntd

Plastic Limit

- moisture content at the point of transition from semi-solid to plastic state.
- moisture content at which the soil crumbles when rolled into threads of 3mm diameter.
- the lower limit of the plastic stage of soil.



Soil Consistency cntd

Plastic Limit Test

Procedure

1. About 15gm of soil passing through No. 40 sieve is mixed with water.
2. The soil is rolled on a glass plate with the hand, until about 3mm in diameter.
3. Mixing and rolling is repeated till the soil shows signs of crumbling when the diameter is 3mm.
4. The water content of the crumbled portion of the thread is determined and is called the plastic limit, PL.

Video: LL & PL determination lab. procedures

Soil Consistency cntd

Plastic Limit Test [from cone penetrometer / fall cone]

- The plastic limit is also determined from fall cone test data plotted on semi-log scale graph with penetration on the horizontal axis.
- It is found by projecting the best fit-straight line backward to intersect the water content axis at a depth of penetration of 1 mm. The water content at this depth of penetration (1 mm) is C.
- The plastic limit is given as $PL = C(2)^m$

where m is the slope (taken as positive) of the best-fit straight line.

EXERCISE 2.4.3 – PLASTIC LIMIT

The results of a fall cone test are shown in the table below.

Cone mass	80-gram cone				
Penetration (mm)	5.5	7.8	14.8	22.0	32.0
Water content (%)	39.0	44.8	52.5	60.3	67

Plot the result with penetration on log scale horizontal axis and water content on log scale vertical axis.

Determine the liquid and plastic limits.

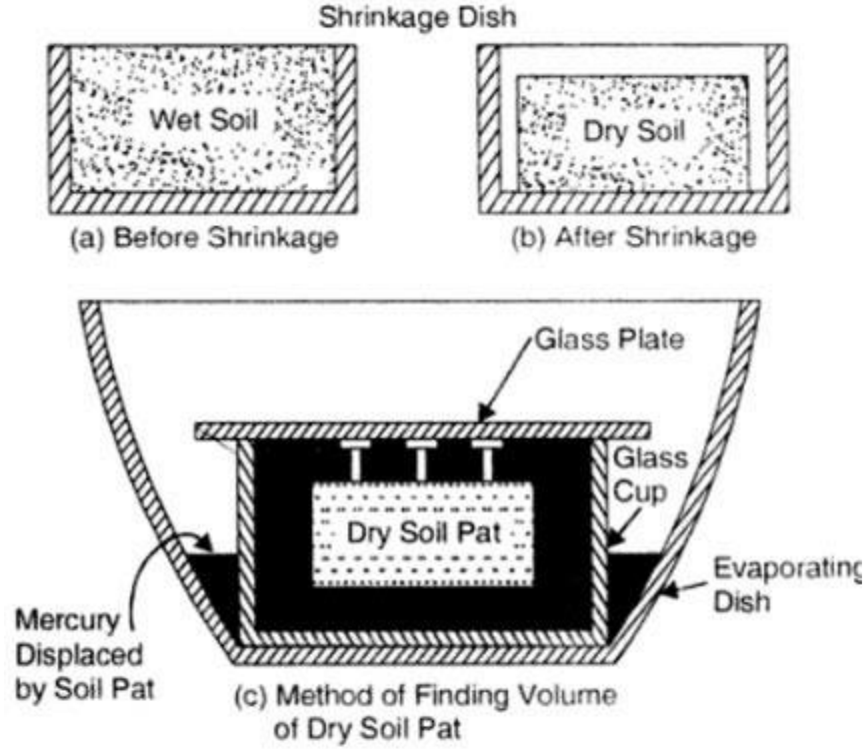
Soil Consistency cntd

Shrinkage Limit

- Moisture content at the point of transition from solid to semi-solid state.
- Soil shrinks as moisture is gradually lost from it.
- With continuing loss of moisture, a stage of equilibrium is reached at which more loss of moisture will result in no further volume change.
- The moisture content at which the volume of the soil mass ceases to change is defined as the shrinkage Limit, SL.

Soil Consistency cntd

- A mass of wet soil, M_1, is placed in a porcelain dish 44.5 mm in diameter and 12.5 mm high and then oven-dried.



APPARATUS OF SHRINKAGE LIMIT DETERMINATION.

- The volume of oven-dried soil is determined by using mercury to occupy the vacant spaces caused by shrinkage.
- The mass of the mercury is determined, and the volume decrease caused by shrinkage can be calculated from the known density of mercury.

Soil Consistency cntd

$$SL = \left(\frac{M_1 - M_2}{M_2} - \frac{V_1 - V_2}{M_2}\frac{\gamma_w}{g}\right) * 100 = \left(\omega - \frac{V_1 - V_2}{M_2}\frac{\gamma_w}{g}\right) * 100$$

where M_1 *is the mass of the wet soil,* M_2 *is the mass of the oven − dried soil,* ω *is water content (not in percentage),* V_1 *is the volume of wet soil,* V_2 $\left(= \frac{mass\ of\ mercury}{density\ of\ mercury}\right)$ *is the volume of the oven − dried soil, and* g *is the acceleration due to gravity.*

The linear shrinkage ratio: $\boldsymbol{LS = 1 - \sqrt[3]{\frac{V_2}{V_1}}}$

The shrinkage ration: $\boldsymbol{SR = \frac{M_2 g}{V_2 \gamma_w}}$

EXERCISE 2.4.4 – SHRINKAGE LIMIT

The following results were recorded in a shrinkage limit test using mercury. Determine the shrinkage limit.

Mass of container (g)	17.5
Mass of wet soil and container (g)	78.1
Mass of dish (g)	130.0
Mass of dish and displaced mercury (g)	462.0
Mass of dry soil and container (g)	64.4

Soil Consistency cntd

Shrinkage Index, SI=PL-SL

- The range of water content from the plastic limit to the shrinkage limit.

Empirical Expression for SL

The shrinkage limit can be estimated from the liquid limit and plasticity index by the following empirical expression:

$$SL = 46.4\left(\frac{LL + 45.5}{PI + 46.4}\right) - 43.5$$

where LL and PI are in percent.

Soil Consistency cntd

Plasticity Index, PI = LL - PL

- PI is the range of water content over which the soil exhibits plasticity.
- The greater the difference between LL and PL, the greater the plasticity.
- Cohesionless soil has 0 PI.

Non-plastic.

- High PI and LL are highly

plastic or fat.

Plasticity Index	Plasticity
0	Non-plastic
< 7	Low plastic
7 – 17	Medium
> 17	Highly plastic

Soil Consistency cntd

Liquidity Index (water plasticity index), $\mathbf{LI = \frac{\omega - PL}{PI}}$

- indicate the consistency of undisturbed soils.

Relative Consistency, $\mathbf{C_r = \frac{LL - \omega}{PI}}$

- indicate the proximity of its natural water content to its PL. NB LI + Cr = 1

Consistency	LI
Semi solid/solid state	-ve
Very stiff state w=PL	0
Very soft state w=LL	1
Liquid state (when disturbed)	> 1

Consistency	Cr
w=LL, soft, neg. shear strength	0
W=PL, firm	1
Semi-solid state, Strong	>1
w >LL	-Ve

Soil Consistency cntd

Activity, A $$A = \frac{PI}{P_{200}}$$

- where PI- Plasticity Index , P_{200} – Clay fraction
- used to separate the effect of type and amount of clays in a soil on the Atterberg limits.
    - Normal clays: 0.75<A<1.25
    - Inactive clays: A<0.75
    - Active clays: A>1.25
- High activity entails large volume change when wetted, large shrinkage when dried & high reactivity (chemically)

EXERCISE 2.4.5 – INDICES

Determine the plasticity index and the liquidity index of the soil considered in EXERCISE 2.4.3 if the natural water content is 46%.

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Galatoma!