FACULTY OF ENGINEERING AND TECHNOLOGY

DEPARTMENT OF MINING AND WATER RESOURCES ENGINEERING

BACHELOR OF SCIENCE IN WATER RESOURCES ENGINEERING

2024 – 2025 LECTURES NOTES FOR

WAR 2105 SOIL MECHANICS (4 CU)

prepared by: Joseph KUSEMERERWA

Contact Details: 0781632861

                          kujosoft@gmail.com

1.0 CHAPTER ONE. PYSICAL AND CHEMICAL PROPERTIES OF SOIL

1.1 Introduction to soil mechanics

1.1.1 Definitions

Soil can be defined in various ways depending upon the professional field (Agriculturalist, Geologist, and Engineers) in which it is being considered. **To an Agriculturalist,** Soil is the substance existing on the earth's surface, which grows and develops plant life.

To a Geologist, Soil is the material in the relative thin surface zone within which roots occur, and all the rest of the crust is grouped under the term rock irrespective of its hardness.

To an Engineer, soil is the unaggregated or uncemented deposits of minerals and or organic particles/fragments covering large portions of earth's crust (punmia et al, 2005). The particles include: Boulders, sand, gravel, clay, and silt while organic particles are the ones having residues of dead animals and plants.

Soil can also be defined as a naturally-occurring mixture of mineral and organic ingredients with a definite form, structure, and composition.

To an Engineer, it is a material that can be:

i. Built on: foundations to buildings, bridges.

ii.Built in: tunnels, culverts, basements. iii. Built with: roads, runways, embankments, dams. iv. Supported: retaining walls, terraces, quays (water side platforms).

1.1.1 Soil Mechanics definition.

Soil mechanics is the application of the **laws of mechanics** and **hydraulics** to engineering problems dealing with sediments and other unconsolidated accumulations of solid particles produced by mechanical and chemical disintegration of rocks (punmia et al, 2005). Mechanical or physical weathering of rocks is caused by such factors as periodical temperature changes and impact and splitting action caused by flowing water, ice, and wind. Chemical weathering is caused by oxidation, hydration, carbonation, and leaching by organic acids and water.

1.2 Description and classification of soil

Description of soil is a statement portraying the physical nature and state of the soil. It can be a description of a sample, or a soil in situ. It is arrived at using visual examination, simple tests, observation of site conditions and geological history.

Soil classification is the separation of soil into classes or groups each having similar characteristics and potentially similar behaviour. A classification for engineering purposes should be based mainly on mechanical properties, e.g. permeability, stiffness, strength. The class to which a soil belongs can be used in its description.

1.2.1 Basic characteristics of soil

Soils consist of grains (mineral grains, rock fragments, etc.) with water and air in the voids between grains. The water and air contents are readily altered by changes in conditions and location: soils can be perfectly dry (have no water content) or be fully saturated (have no air content) or be partly saturated (with both air and water present). Although the size and shape of the solid (granular) content rarely changes at a given point, they can vary considerably from point to point. First of all, when we consider soil as an engineering material, it is not a coherent solid material like steel and concrete, but is a

particulate material. It is important to understand the significance of particle size, shape and composition, and of a soil's internal structure or fabric.

a) Size range of grains

Figure 1: Aid to size identification (BSCS)

The range of particle sizes encountered in soil is very large: from boulders with a controlling dimension of over 200mm down to clay particles less than 0.002mm. Some clay that contains particles less than 1 mm in size behaves as colloids, i.e. do not settle in water due solely to gravity and density.

In the British Soil Classification System (BSCS), soils are classified into named Basic soil type groups according to size, and the groups further divided into coarse, medium and fine sub-groups as shown below:

Very coarse soils	BOULDERS		> 200 mm
	COBBLES		60 - 200 mm
Coarse soils	G GRAVEL	Coarse	20 - 60 mm
		Medium	6 - 20 mm
		Fine	2 - 6 mm
	S SAND	Coarse	0.6 - 2.0 mm
		Medium	0.2 - 0.6 mm
		Fine	0.06 - 0.2 mm
Fine soils	M SILT	Coarse	0.02 - 0.06 mm
		Medium	0.006 - 0.02 mm
		Fine	0.002 - 0.006 mm
	C CLAY		< 0.002 mm

Soils possess a number of physical characteristics which can be used as aids to size identification in the field. A handful of soil rubbed through the fingers can yield the following:

Sand (and coarser) particles are visible to the naked eye.

Silt particles become dusty when dry and are easily brushed off hands and boots. **Clay** particles are greasy and sticky when wet and hard when dry, and have to be scraped or washed off hands and boots.

b) Shape of grains

The majority of soils may be regarded as either sands or clays.

Sands include gravelly sands and gravel-sands. Sand grains are generally broken rock particles that have been formed by physical weathering, or they are the resistant components of rocks broken down by chemical weathering. Sand grains generally have a **rotund** (rounded) shape.

Clays include silty clays and clay-silts; there are few pure types of silt (e.g. areas formed by windblown Loess (fine grained soils)). Clay grains are usually the product of chemical weathering or rocks and soils. Clay particles have a **flaky** shape.

There are major differences in engineering behaviour between sands and clays (for example in permeability, compressibility, shrinking/swelling potential). The shape and size of the soil grains has an important bearing on these differences.

Shape characteristics of sand grains

Sand and larger-sized grains are **rotund**. Coarse soil grains (silt-sized, sandsized and larger) have different shape characteristics and surface roughness depending on the amount of wear during transportation (by water, wind or ice), or after crushing in manufactured aggregates. They have a relatively low specific surface (surface area).

i. Rounded: Water or air worn; transported sediments ii. Irregular: Irregular shape with round edges; glacial sediments (sometimes sub-divided into 'sub-rounded' and 'sub-angular') iii. Angular: Flat faces and sharp edges; residual soils, grits iv. Flaky: Thickness small compared to length/breadth; clays

v. Elongated: Length larger than breadth/thickness; scree (fine grains at hill bases), broken flagstone

Vi. Flaky & Elongated: Length>Breadth>Thickness; broken schist (rock that splits into layers) and slates

Shape characteristics of clays grains

Clay particles are **flaky**. Their thickness is very small relative to their length & breadth, in some cases as thin as 1/100th of the length. They therefore

have high to very high specific surface values. These surfaces carry a small negative electrical charge that will attract the positive end of water molecules. This charge depends on the soil mineral and may be affected by an electrolyte in the pore water. This causes some additional forces between the soil grains which are proportional to the specific surface. Thus, a lot of water may be held as adsorbed water within clay mass.

c) Structure or fabric

Natural soils are rarely the same from one point in the ground to another. The content and nature of grains varies, but more importantly, so does the arrangement of these. The arrangement and organization of particles and other features within a soil mass is termed its **structure** or **fabric.** This includes bedding orientation, stratification, layer thickness, the occurrence of joints and fissures (long crack), the occurrence of voids, tree roots and nodules, the presence of cementing or bonding agents between grains. Structural features can have a major influence on in situ properties such as

i.   Vertical and horizontal permeability will be different in alternating layers of fine and coarse soils.

ii.   The presence of fissures affects some aspects of strength.   iii. The presence of layers or lenses of different stiffness can affect stability. iv. The presence of cementing or bonding influences strength and stiffness.

Reading Assignment: What is specific surface in regards to soil characteristics

1.2.2 Origins, formation and mineralogy

Soils are the results of geological events (except for the very small amount produced by man). The nature and structure of a given soil depends on the geological processes that formed it. Geological processes include:

i. **Breakdown** of parent rock: weathering, decomposition, erosion.

ii.**Transportation** to site of final deposition: gravity, flowing water, ice, wind.

   iii. **Environment** of final deposition: flood plain, river terrace, glacial

moraine, **lacustrine iv. Subsequent conditions** of loading and drainage - little or no **surcharge**, heavy surcharge due to ice or overlying deposits, change from saline to freshwater, leaching, contamination.

Origins of soils from rocks

All soils originate, directly or indirectly, from solid rocks in the Earth's crust: The rocks are grouped as follows:

a)   **Igneous rocks**. Crystalline bodies of cooled magma e.g. granite, basalt, dolerite, gabbro, syenite, and porphyry

b)   **Sedimentary rocks**. Layers of consolidated and cemented sediments, mostly formed in bodies of water (seas, lakes, etc.) e.g. limestone, sandstones, mudstone, shale, conglomerate

c)   **Metamorphic rocks**. Formed by the alteration of existing rocks due to heat from igneous intrusions (e.g. marble, quartzite, and hornfels) or pressure due to crustal movement (e.g. slate, schist, gneiss

Weathering of rocks

a)   **Physical weathering.** Physical or mechanical processes taking place on the Earth's surface, including the actions of water, frost, temperature changes, wind and ice; cause disintegration and wearing. The products are mainly coarse soils (silts, sands and gravels). Physical weathering produces Very Coarse soils and Gravels consisting of broken rock particles, but Sands and Silts will be mainly consists of mineral grains.

b)   **Chemical weathering**. Chemical weathering occurs in wet and warm conditions and consists of degradation by decomposition and/or alteration caused by dissolution, carbonation, oxidation or hydrolysis of rocks. The results of chemical weathering are generally fine soils with separate mineral grains, such as Clays and Clay-Silts. The type of clay mineral depends on the parent rock and on local drainage. Some minerals, such as quartz, are resistant to the chemical weathering and remain unchanged. Minerals include the following:

1) **Quartz.** A resistant and enduring mineral found in many rocks (e.g. granite, sandstone). It is the principal constituent of sands and silts, and the most abundant soil mineral. It occurs as equidimensional hard grains.

2) **Haematite**. A red iron (ferric) oxide: resistant to change, results from extreme weathering. It is responsible for the widespread red or pink colouration in rocks and soils. It can form cement in rocks, or a duricrust (hard soil crust) in soils in arid climates.

3) **Micas**. Flaky minerals present in many igneous rocks. Some are resistant, e.g. muscovite; some are broken down, e.g. biotite.

4) **Clay minerals**. These result mainly from the breakdown of feldspar minerals. They are very flaky and therefore have very large surface areas. They are major constituents of clay soils, although clay *soil* also contains silt sized particles. Clay minerals are produced mainly from the chemical weathering and decomposition of feldspars, such as orthoclase and plagioclase, and some mica. They are small in size and very flaky in shape. The key to some of the properties of clay soils, e.g. plasticity, compressibility, swelling/shrinkage potential, lies in the structure of clay minerals.

There are three main groups of clay minerals:

i) **Kaolinites**, dickite and nacrite formed by the decomposition of orthoclase feldspar (e.g. in granite); kaolin is the principal constituent in china clay and ball clay.

ii) **Illites** and glauconite are the commonest clay minerals; formed by the decomposition of some micas and feldspars; predominant in marine clays and shales (e.g. London clay, Oxford clay).

iii) **Montmorillonites.** (also called smectites or fullers' earth minerals) (include calcium and sodium momtmorillonites, bentonite and vermiculite) formed by the alteration of basic igneous rocks containing silicates rich in Ca and Mg; weak linkage by cations (e.g. Na^+, Ca^{++}) results in high swelling/shrinking potential

Transportation and deposition

The effects of weathering and transportation largely determine the basic **nature** of the soil (i.e. the size, shape, composition and distribution of the grains). The environment into which deposition takes place, and subsequent geological events that take place there, largely determine the **state** of the soil, (i.e. density, moisture content) and the **structure** or fabric of the soil (i.e. bedding, stratification, occurrence of joints or fissures, tree roots, voids, etc.)

Transportation: it is due to combinations of gravity, flowing water or air, and moving ice. In water or air: grains become sub-rounded or rounded, grain sizes are sorted, producing poorly-graded deposits. In moving ice: grinding and crushing occur, size distribution becomes wider, deposits are wellgraded, ranging from rock flour to boulders.

Deposition: In flowing water, larger particles are deposited as velocity drops, e.g. gravels in river terraces, sands in floodplains and estuaries, silts and clays in lakes and seas. In still water: horizontal layers of successive sediments are formed, which may change with time, even seasonally or daily. Examples of deposits include:

i. Deltaic & shelf deposits: often vary both horizontally and vertically.

ii.From glaciers, deposition varies from well-graded basal tills and boulder clays to poorly-graded deposits in moraines and outwash fans.

iii.　In arid conditions: scree material is usually poorly-graded and lies on slopes.　iv. Windblown Loess is generally uniformly-graded and false-bedded.

1.2.3 Grading or classification

(a) BS (British standards) system for description and classification

BS 5930 Site Investigation recommends the terminology and a system for describing and classifying soils for engineering purposes. Without the use of a satisfactory system of description and classification, the description of materials found on a site would be meaningless or even misleading, and it would be difficult to apply experience to future projects.

A recommended protocol for describing a soil deposit uses **nine** characteristics; these should be written in the following order:

i.   **Compactness**. e.g. loose, dense, slightly cemented

ii. **Bedding structure**. E.g. homogeneous or stratified; dip, orientation

iii. **Discontinuities**. spacing of beds, joints, fissures

iv. **Weathered state** degree of weathering

v.   **Colour** main body colour, mottling

vi. **Grading or consistency** e.g. well-graded, poorly-graded; soft, firm, hard

vii. **Soil name** e.g. GRAVEL, SAND, SILT, CLAY; (upper case letters) plus silty-, gravelly-, with-fines, etc. as appropriate

viii. **Soil class.** (BSCS) designation (for roads & airfields) e.g. SW = wellgraded sand **ix. Geological stratigraphic name**, **example:**

   (i) Loose homogeneous reddish-yellow poorly-graded medium sand (SP), Flood plain alluvium

   (ii) Dense fissured unweathered greyish-blue firm clay.

Definitions of terms used in description

A table is given in BS 5930 Site Investigation setting out a recommended field identification and description system. The following are some of the terms listed for use in soil descriptions:

i.   **Particle shape** angular, sub-angular, sub-rounded, rounded, flat, elongate

ii. **Compactness,** loose, medium dense, dense

iii. **Bedding structure**, homogeneous, stratified, inter-stratified

iv. **Bedding spacing,** massive(>2m), thickly bedded (2000-600 mm), medium bedded (600-200 mm), thinly bedded (200-60 mm), very thinly bedded (60-20 mm), laminated (20-6 mm), thinly laminated (<6 mm).

v.   **Discontinuities,** i.e. spacing of joints and fissure: very widely spaced (>2m), widely spaced (2000-600 mm), medium spaced (600-200 mm),

closely spaced (200-60 mm), very closely spaced (60-20 mm), extremely closely spaced (<20 mm).

vi. **Colours,** red, pink, yellow, brown, olive, green, blue, white, grey, black

vii. **Consistency,** very soft (exudes between fingers), soft (easily mouldable), firm (strong finger pressure required), stiff (can be indented with fingers, but not moulded) very stiff (indented by sharp object), hard (difficult to indent).

viii. **Grading,** well graded (wide size range), uniform (very narrow size range), poorly graded (narrow or uneven size range).

Composite soils, In sands and gravels: slightly clayey or silty (<5%), clayey or silty (5-15%), very clayey or silty(>15%) In clays and silts: sandy or gravelly (35-65%)

British Soil Classification System

The recommended standard for soil classification is the **British Soil Classification System**, and this is detailed in BS 5930 Site Investigation. It's essential structure is as follows:

Soil group		Symbol		Recommended name
Coarse soils			Fines %	
GRAVEL	G	GW	0 – 5	Well-graded GRAVEL
		GPu/GPg	0 – 5	Uniform/poorly-graded GRAVEL
	G-F	GWM/GWC	5 – 15	Well-graded silty/clayey GRAVEL
		GPM/GPC	5 – 15	Poorly graded silty/clayey GRAVEL
	GF	GML, GMI...	15 – 35	Very silty GRAVEL [plasticity sub-group...]
		GCL, GCI...	15 – 35	Very clayey GRAVEL [..symbols as below]

	S	SW	0 – 5	Well-graded SAND
SAND		SPu/SPg	0 – 5	Uniform/poorly-graded SAND
	S-F	SWM/SWC	5 – 15	Well-graded silty/clayey SAND
		GPM/GPC	5 – 15	Poorly graded silty/clayey SAND
	SF	SML, SMI...	15 – 35	Very silty SAND [plasticity subgroup...]
		SCL, SCI...	15 – 35	Very clayey SAND [..symbols as below]
Fine soils		**>35% fines**	**Liquid limit%**	
SILT	M	MG		Gravelly SILT
		MS		Sandy SILT
		ML, MI...		[Plasticity subdivisions as for CLAY]
CLAY	C	CG		Gravelly CLAY
		CS		Sandy CLAY
		CL	<35	CLAY of low plasticity
		CI	35 – 50	CLAY of intermediate plasticity
		CH	50 – 70	CLAY of high plasticity
		CV	70 – 90	CLAY of very high plasticity
		CE	>90	CLAY of extremely high plasticity
Organic soils	O			[Add letter 'O' to group symbol]

Peat	Pt			[Soil predominantly fibrous and organic]

The recommended standard for soil classification is the British Soil Classification System **(BSCS)**.

a) Classification of coarse soils

Coarse soils are classified principally on the basis of particle size and grading.

Very coarse soils	BOULDERS		> 200 mm
	COBBLES		60 - 200 mm
Coarse soils	**G** GRAVEL	Coarse	20 - 60 mm
		Medium	6 - 20 mm
		Fine	2 - 6 mm
	S SAND	Coarse	0.6 - 2.0 mm
		Medium	0.2 - 0.6 mm
		Fine	0.06 - 0.2 mm

Particle size tests

The aim is to measure the distribution of particle sizes in the sample. When a wide range of sizes is present, the sample will be sub-divided, and separate tests carried out on each sub-sample. Particle size distribution can be done through a number of ways including wet sieving, dry sieving, and sedimentation tests.

1) Wet sieving to separate fine grains from coarse grains is carried out by washing the soil specimen on a 60mm sieve mesh.

2) **Dry sieving** analyses can only be carried out on particles > 60 mm. Samples (with fines removed) are dried and shaken through a nest of sieves of descending size.

3) **Sedimentation** is used only for fine soils. Soil particles are allowed to settle from a suspension. The decreasing density of the suspension is measured at time intervals. Sizes are determined from the settling velocity and times recorded. Percentages between sizes are determined from density differences.

Particle-size analysis

The cumulative percentage quantities finer than certain sizes (e.g. passing a given size sieve mesh) are determined by weighing. Points are then plotted of **% finer (passing)** against **log size**. A smooth S-shaped curve drawn through these points is called a **grading curve**. The position and shape of the grading curve determines the soil class. Geometrical **grading characteristics** can be determined also from the grading curve.
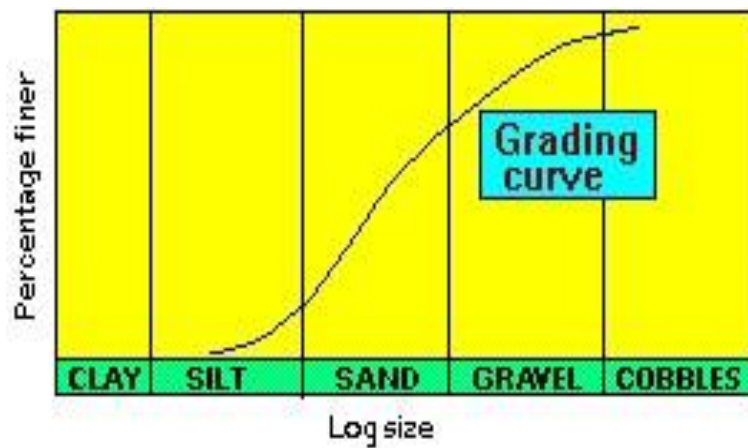
Typical grading curves
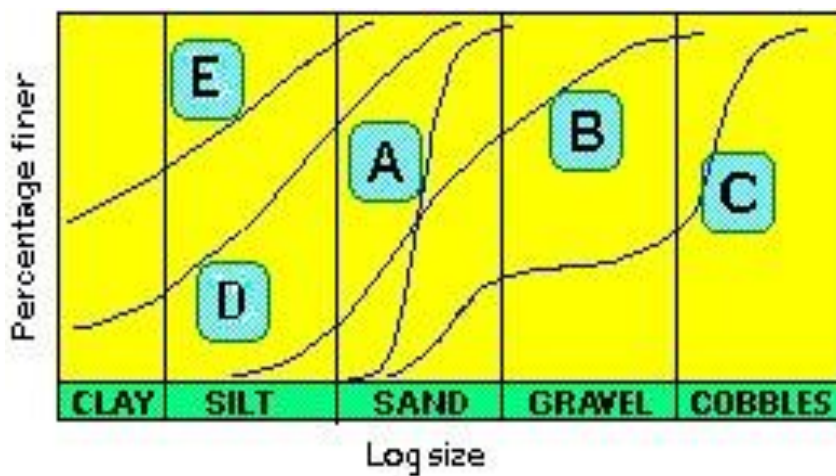
Both the position and the shape of the grading curve for a soil can aid its identity and description.

Some typical grading curves are shown in the figure:

A - a poorly-graded medium sand (probably estuarine or flood-plain alluvium)
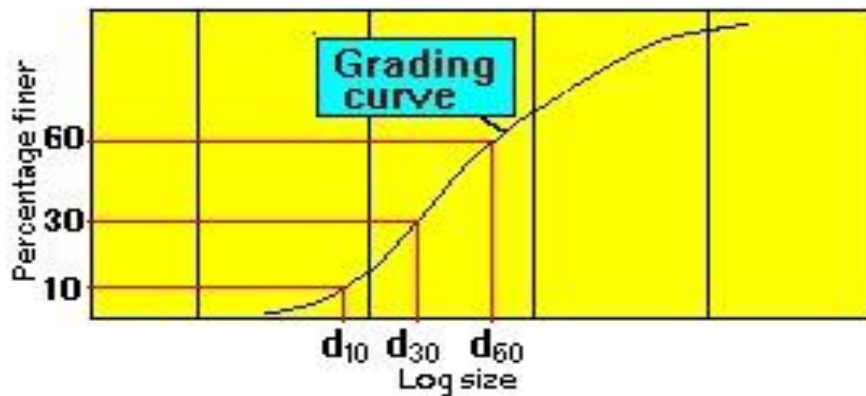
B - a well-graded gravel-sand (i.e. equal amounts of gravel and sand)

C   -   a   gap-graded cobbles-sand

D   -   a   sandy   silt   (perhaps   a   deltaic   or
                 estuarine   silt)

E   -   a   typical   silty   clay.

Grading characteristics

A grading curve is a useful aid to soil description. Grading curves are often included in ground investigation reports. Results of grading tests can be tabulated using geometric properties of the grading curve. These properties are called **grading characteristics**

First of all, three points are located on the grading curve: d_{10} = the maximum size of the smallest 10% of the sample d_{30} = the maximum size of the smallest 30% of the sample

d_{60} = the maximum size of the smallest 60% of the sample

From these the grading characteristics are calculated: **Effective** d_{10} **size**

Uniformity   coefficient

C_u = d_{60} / d_{10}

Coefficient   of   gradation

$C_k = d_{30}^2 / d_{60} \, d_{10}$

Both C_u and C_k will   be   1   for   a single-sized   soil
C_u >   5   indicates   a   well-graded   soil

C_u <   3   indicates   a   uniform   soil

C_k between   0.5   and   2.0   indicates   a   well-graded   soil
C_k < 0.1 indicates a possible gap-graded soil

Sieve analysis example

The results of a dry-sieving test are given below, together with the grading analysis and grading curve. Note carefully how the tabulated results are set out and calculated. The grading curve has been plotted on special semilogarithmic paper; you can also do this analysis using a spreadsheet.

Sieve mesh size (mm)	Mass retained (g)	Percentage retained	Percentage finer (passing)
14.0	0	0	100.0
10.0	3.5	1.2	98.8
6.3	7.6	2.6	86.2
5.0	7.0	2.4	93.8
3.35	14.3	4.9	88.9
2.0	21.1	7.2	81.7
1.18	56.7	19.4	62.3
0.600	73.4	25.1	37.2
0.425	22.2	7.6	29.6
0.300	26.9	9.2	20.4
0.212	18.4	6.3	14.1
0.150	15.2	5.2	8.9
0.063	17.5	6.0	2.9

|			
Pan	8.5	2.9	
TOTAL	292.3	100.0	
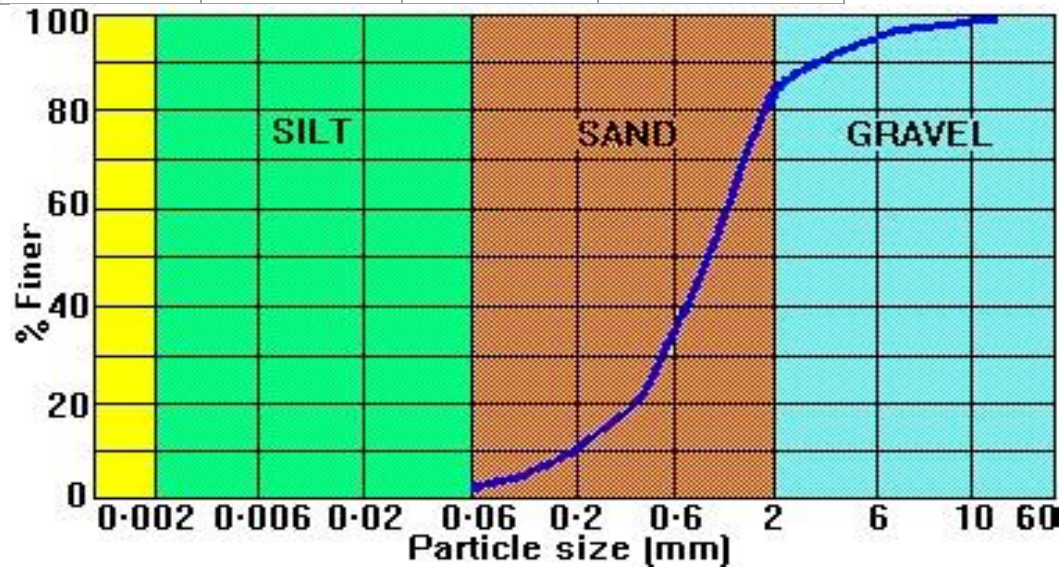
The soil comprises: 18% gravel, 45% coarse sand, 24% medium sand, 10% fine sand, 3% silt, and is classified therefore as: a **well-graded gravelly sand**
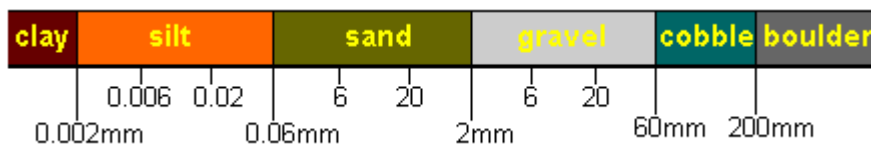
Classification of fine soils:
In the case of fine soils (e.g. clays and silts), it is the shape of the particles rather than their size that has the greater influence on engineering properties. Clay soils have flaky particles to which water adheres, thus imparting the property of **plasticity**.

1) Consistency limits and plasticity
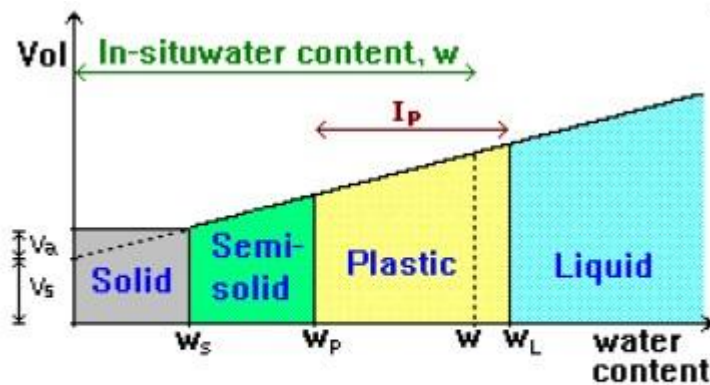
Consistency varies with the water content of the soil. The consistency of a soil can range from (dry) solid to semi-solid to plastic to liquid (wet). The water contents at which the consistency changes from one state to the next are called **consistency limits** (or **Atterberg limits**). Two of these are utilized in the classification of fine soils:

The liquid limit (LL) is the water content where a soil changes from plastic to liquid behavior.
The plastic limit (PL) is the water content where soil starts to exhibit plastic behavior. A thread of soil is at its plastic limit when it is rolled to a diameter of 3 mm and begins to crumble. To improve consistency, a 3 mm diameter rod is often used to gauge the thickness of the thread when conducting the test.

Plasticity index
The consistency of most soils in the ground will be plastic or semi-solid. Soil strength and stiffness behaviour are related to the range of plastic consistency. The range of water content over which a soil has a plastic consistency is termed the **Plasticity Index** (IP or PI).

IP= liquid limit – plastic limit
   =W_L-W_P

The plasticity chart and classification
In the BSCS fine soils are divided into ten classes based on their measured plasticity index and liquid limit values: Clays are distinguished from silts, and five divisions of plasticity are defined:

Low plasticity	$w_L = \, <35\%$
Intermediate plasticity	$w_L = 35 - 50\%$
High plasticity	$w_L = 50 - 70\%$
Very high plasticity	$w_L = 70 - 90\%$
Extremely high plasticity	$w_L = \, >90\%$

Activity

So-called 'clay' soils are not 100% clay. There are proportions of clay mineral flakes (< 2 mm size) in a fine soil which affects its current state, particularly its tendency to swell and shrink with changes in water content. The degree of plasticity related to the clay mineral content is called the **activity** of the soil.
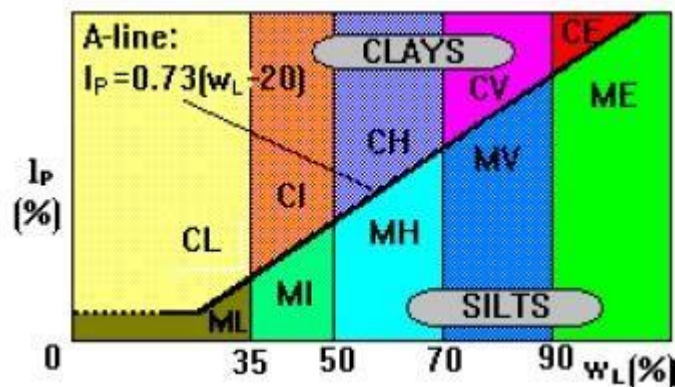
Activity = IP / (% clay mineral particles) Some typical values are:

Mineral	Activity	Soil	Activity
Muscovite	0.25	Kaolin clay	0.4-0.5
Kaolinite	0.40	Glacial clay and loess	0.5-0.75
Illite	0.90	Most British clays	0.75-1.25
Montmorillonite	> 1.25	Organic estuarine clay	> 1.25

1.2.4 Specific gravity

Specific gravity (G_s) is a property of the mineral or rock material forming soil grains.

It is defined as;

$$G_S = \frac{\text{mass of a soil grain}}{\text{mass of an equal volume of water}}$$

Method   of   measurement.

For fine soils a 50 ml density bottle may be used; for coarse soils a 500 ml or 1000 ml jar. The jar is weighed empty (M_1). A quantity of dry soil is placed in the jar and the jar weighed (M_2). The jar is filled with water, air removed by stirring, and weighed again (M_3). The jar is emptied, cleaned and refilled with water - and weighed again (M_4).

$$G_S = \frac{\text{Mass of soil}}{\text{Mass of water displaced by soil}}$$
$$= \frac{M_2 - M_1}{(M_4 - M_1) - (M_3 - M_2)}$$

1.3 Physical and chemical properties of soil

1.3.1 Soil chemical properties

Major Elements

Eight chemical elements comprise the majority of the mineral matter in soils. Of these eight elements, oxygen, a negatively-charged ion **(anion)** in crystal structures, is the most prevalent on both a weight and volume basis. The next most common elements, all positively-charged ions **(cations)**, in decreasing order are silicon, aluminum, iron, magnesium, calcium, sodium, and potassium. Ions of these elements combine in various ratios to form different minerals. More than eighty other elements also occur in soils and the earth's crust, but in much smaller quantities.

Soils are chemically different from the rocks and minerals from which they are formed in that soils contain less of the water soluble weathering products, calcium, magnesium, sodium, and potassium, and more of the relatively insoluble elements such as iron and aluminum. Old, highly weathered soils normally have high concentrations of aluminum and iron oxides.

The organic fraction of a soil, although usually representing much less than 10% of the soil mass by weight, has a great influence on soil chemical

properties. **Soil organic matter** is composed chiefly of carbon, hydrogen, oxygen, nitrogen and smaller quantities of sulfur and other elements. The organic fraction serves as a reservoir for the plant essential nutrients, nitrogen, phosphorus, and sulfur, increases soil water holding and cation exchange capacities, and enhances soil aggregation and structure.

The most chemically active fraction of soils consists of colloidal clays and organic matter. Colloidal particles are so small (< 0.0002 mm) that they remain suspended in water and exhibit a very large surface area per unit weight. These materials also generally exhibit net negative charge and high adsorptive capacity. Several different silicate clay minerals exist in soils, but all have a layered structure. Montmorillonite, vermiculite, and micaceous clays are examples of **2:1 clays**, while kaolinite is a **1:1 clay** mineral. Clays having a layer of aluminum oxide (octahedral sheet) sandwiched between two layers of silicon oxide (tetrahedral sheets) are called 2:1 clays. Clays having one tetrahedral sheet bonded to one octahedral sheet are termed 1:1 clays.

Cation Exchange

Silicate clays and organic matter typically possess net negative charge because of cation substitutions in the crystalline structures of clay and the loss of hydrogen cations from functional groups of organic matter. Positivelycharged cations are attracted to these negatively-charged particles, just as opposite poles of magnets attract one another. **Cation exchange** is the ability of soil clays and organic matter to adsorb and exchange cations with those in soil solution (water in soil pore space). A dynamic equilibrium exists between adsorbed cations and those in soil solution. Cation adsorption is reversible if other cations in soil solution are sufficiently concentrated to displace those attracted to the negative charge on clay and organic matter surfaces. The quantity of cation exchange is measured per unit of soil weight and is termed **cation exchange capacity**. Organic colloids exhibit much greater cation exchange capacity than silicate clays. Various clays also exhibit different exchange capacities. Thus, cation exchange capacity of soils is

dependent upon both organic matter content and content and type of silicate clays.

Cation exchange capacity is an important phenomenon for two reasons:

1. Exchangeable cations such as calcium, magnesium, and potassium are readily available for plant uptake and
2. Cations adsorbed to exchange sites are more resistant to **leaching**, or downward movement in soils with water.

Movement of cations below the rooting depth of plants is associated with weathering of soils. Greater cation exchange capacities help decrease these losses. Pesticides or organics with positively charged functional groups are also attracted to cation exchange sites and may be removed from the soil solution, making them less subject to loss and potential pollution.

Calcium (Ca^{++}) is normally the predominant exchangeable cation in soils, even in acid, weathered soils. In highly weathered soils, such as oxisols, aluminum (Al^{+3}) may become the dominant exchangeable cation.

The energy of retention of cations on negatively charged exchange sites varies with the particular cation. The order of retention is: aluminium > calcium > magnesium > potassium > sodium > hydrogen. Cations with increasing positive charge and decreasing hydrated size are most tightly held. Calcium ions, for example, can rather easily replace sodium ions from exchange sites. This difference in replace ability is the basis for the application of gypsum ($CaSO_4$) to reclaim sodic soils (those with $\geq$ 15% of the cation exchange capacity occupied by sodium ions). Sodic soils exhibit poor structural characteristics and low infiltration of water.

The cations of calcium, magnesium, potassium, and sodium produce an alkaline reaction in water and are termed bases or **basic cations**. Aluminum and hydrogen ions produce acidity in water and are called **acidic cations**. The percentage of the cation exchange capacity occupied by basic cations is

called **percent base saturation**. The greater the percent base saturation, the higher the soil pH.

Soil pH

Soil pH is probably the most commonly measured soil chemical property and is also one of the more informative. Like the temperature of the human body, soil pH implies certain characteristics that might be associated with a soil. Since pH (the negative log of the hydrogen ion activity in solution) is an inverse, or negative, function, soil pH decreases as hydrogen ion, or acidity, increases in soil solution. Soil pH increases as acidity decreases.

A soil pH of 7 is considered neutral. Soil pH values greater than 7 signify alkaline conditions, whereas those with values less than 7 indicate acidic conditions. Soil pH typically ranges from 4 to 8.5, but can be as low as 2 in materials associated with pyrite oxidation and acid mine drainage. In comparison, the pH of a typical cola soft drink is about 3.

Soil pH has a profound influence on plant growth. Soil pH affects the quantity, activity, and types of microorganisms in soils which in turn influence decomposition of crop residues, manures, sludges and other organics. It also affects other nutrient transformations and the solubility, or plant availability, of many plant essential nutrients. Phosphorus, for example, is most available in slightly acid to slightly alkaline soils, while all essential micronutrients, except molybdenum, become more available with decreasing pH. Aluminum, manganese, and even iron can become sufficiently soluble at pH < 5.5 to become toxic to plants. Bacteria which are important mediators of numerous nutrient transformation mechanisms in soils generally tend to be most active in slightly acid to alkaline conditions.

Summary
i.   A measure of the acidity or alkalinity of a soil.
ii.   Neutral = 7.0
iii.   Acidic < 7.0

iv. Alkaline > 7.0

v. Logarithmic scale which means that a 1-unit drop in pH is a 10-fold increase in acidity.

Soil pH and plant growth

i. Affects availability of plant nutrients (in general, optimal pH is between 5.5-7.5) ii. Low pH soils (<6.0) results in an increase in Al. Aluminum is toxic to plants

iii. Affects availability of toxic metals (in general, more available in acidic soils)

iv. Affects the activity of soil microorganisms, thus affecting nutrient cycling and disease risk

Nutrient Availability

Increasing soil pH: Liming materials (pure calcium carbonate or dolomitic lime) will increase soil pH.

1. Lime is a certified organic product
2. Slow-release product. Do not add every year.
3. 15-25 lbs lime per 1000 sq ft is recommended

Wood ashes are another product to raise soil pH. They also are a source of K, Ca, and Mg. Some compost also can increase soil pH.

Gypsum is calcium sulfate. It is not a substitute for lime, and has little effect on soil pH. Gypsum only improves structure in soils that have extremely high sodium contents (rare in the NW).

Decreasing soil pH: Some plants thrive under acidic conditions (ex. rhododendrons, blueberries, and azaleas). Elemental sulfur is often recommended (50 lb S per 1000 sq. ft). Ammonium and ammonium-forming N fertilizers will also result in a decrease in soil pH.

Soil salinity

i. Potential problem in irrigated soils due to high evaporation rates and low annual rainfall leaving salts to accumulate. ii. Salts can come from irrigation water, fertilizers, composts, and manure.

iii.   Salts can be leached by slowly applying excess water.

        o Three inches removes about 50% of the soluble salts. o

        Five inches removes about 90%.

Soil Salinity and Interpretation

Conductivity (mmho/cm)	Interpretation
4 or above	Severe accumulation of salts. May restrict growth of many vegetables and ornamentals.
2 to 4	Moderatre accumulation of salts. Will not restrict plant growth, but may require more frequent irrigation.
less than 2	Low salt accumulation. Will not affect plants.

1.3.2 Soil Physical properties

Soils are porous and open bodies, yet they retain water. They contain mineral particles of many shapes and sizes and organic material which is colloidal (particles so small they remain suspended in water) in character. The solid particles lie in contact one with the other, but they are seldom packed as closely together as possible. The physical properties include texture, structure, consistence, and colour, etc.

(a) Texture

Soil texture refers to classification of soil by the relative proportions of sand, silt, and clay present in the soil (USDA, 1997). USDA uses 12 textural classes which are represented in the figure below. The figure shows a three sided grid with each side representing the content of a particular particle on a scale from 0% to 100%. The bottom line is the sand content, starting at 0% at the bottom right hand corner, and rising to 100% in the bottom left hand corner. Moving clockwise around the triangle, the line from the bottom left corner to the top

point of the triangle is the clay content, starting at 0% in the bottom left corner and rising to 100% at the top.

Continuing clockwise, silt starts at 0% at the top of the triangle and increases to 100% at the bottom right hand corner. By following the percentage lines for sand silt and clay to wherever they meet inside the triangle you can determine which category your soil falls into.

To locate your exact point on the grid you should first calculate the percentage of sand, silt and clay in the total sample without including the organic matter in the total. Then take the percentage of sand as your starting point and, using the bottom of the triangle grid to find the corresponding percentage, begin to draw a line upwards and to the left (parallel with the right hand side of the triangle) at the exact percentage. Next take the percentage of clay and, using the left hand slope of the triangle grid find your percentage point. Starting at that point, draw a line horizontally across (parallel with the bottom of the triangle) toward the right slope of the triangle. It will cross the sand line at some point. The final confirmation that you have done it right is that the percentage of silt, located by the same process on the right hand slope of the triangle and following a line drawn downwards toward the bottom left will cross in the same point as the other two.

Soil triangle showing different soil textures (USDA)
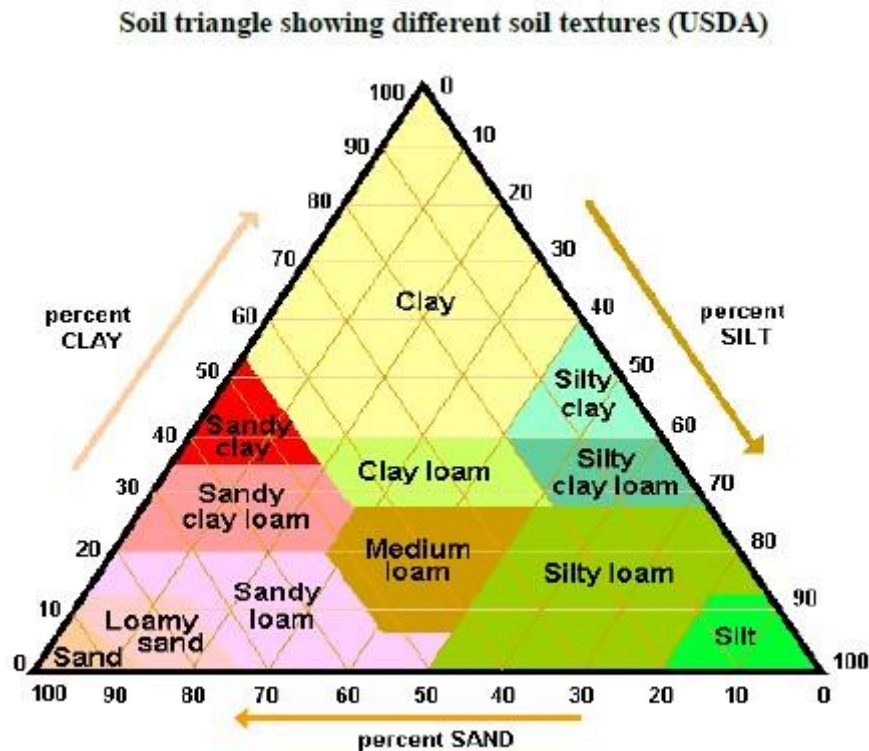
The mineral particles of the soil differ widely in size and can be classified as follows:

Name of the particles	USDA	Distinguishable with naked eye
ROCKS	> 2 mm	Obviously
SAND	0.05 to 2 mm	Easily
SILT	0.002 to 0.05 mm	Barely
CLAY	< 0.002 mm	Impossible

(b) Consistency: The ability of soil particles to stick together. This is related to the amount and type of clay in the soil and is a measure of the soil's behavior under mechanical stress.

(c) Soil structure

This is the arrangement of primary soil particles (sand, silt, and clay) into secondary particles, or units that make up the soil mass (USDA, 1997). These secondary units may be arranged in the soil profile in such a manner as to give a distinctive characteristic pattern. Principal types of soil structure are prismatic, blocky, granular, and massive.

In a prismatic structure, movement of the water in the soil is predominantly vertical and therefore the supply of water to the plant roots is usually poor.

It should be noted that unlike texture, soil structure is not permanent.
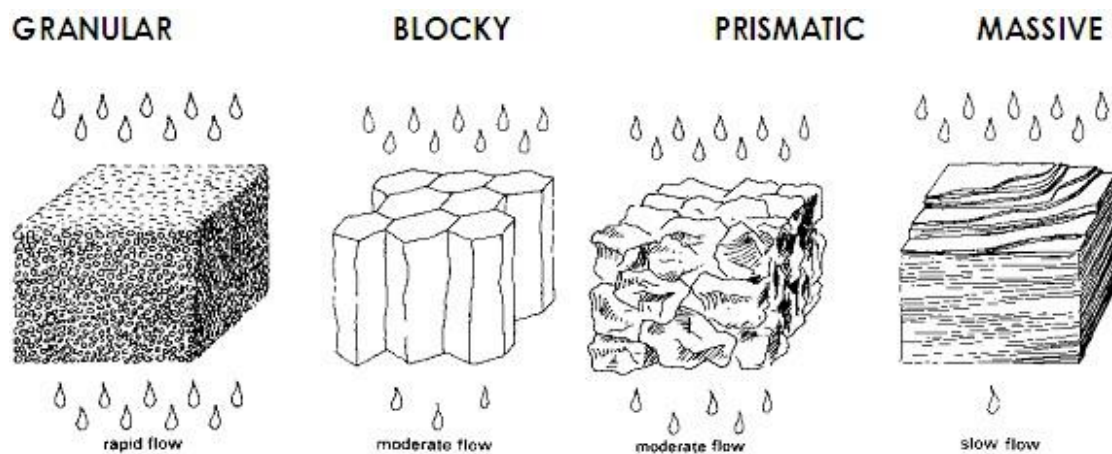
(d)   Bulk density is a measure of the weight of the soil per unit volume (g/cc), usually given on an oven-dry (105° C) basis. Most mineral soils have bulk densities between 1.0 and 2.0.

(e)   Colour: A measure of value, Chroma (visibility), and hue (tint). It indicates a soil's composition and history. Soil colour is determined using the Munsell Colour Chart.

1.4 Soil Composition.

Soil is composed primarily of minerals which are produced from parent material broken into small pieces by weathering. Larger pieces are stones, gravel, and other rock debris. Smaller particles are sand, silt, or clay. Since the original materials vary from place to place, the exact composition of soil

varies according to location. A common example of soil composition by volume might be:

i. 45% Minerals (clay, silt, sand, gravel, stones).

ii. 25% Water (the amount varies depending upon precipitation and the waterholding capacity of the soil). iii. 25% Air (an essential ingredient for living organisms). iv. 5% Organic matter or humus (both living and dead organisms
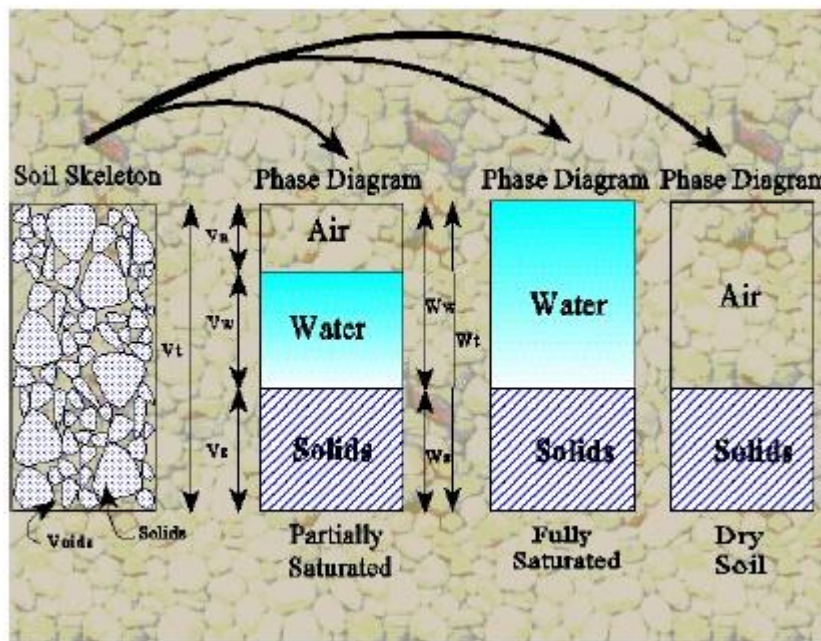
Mineral particles give soil texture. Sand particles range in diameter from 2 mm to 0.05 mm, feel gritty and can be easily seen with the unaided eye. Silt particles are between 0.05 mm and 0.002 mm and feel like flour. Clay particles are smaller than 0.002 mm and cannot be seen with the unaided eye. Because of the small particle size, clay soils can sometimes experience large amounts of expansion and contraction in volume with changes in moisture content. Water and air occupy the pore spaces—the area between soil particles. The final ingredient of a soil is organic matter. Organic matter consists of dead plant and animal material and the billions of living organisms that inhabit soil.

The concern with soil in respect to building is the ability of soil to bear the load of the structure while remaining stable. Ensuring long-term stability

requires proper compaction and consolidation of soil before a permanent load is placed upon it.

1.4.1 MASS-VOLUME RELATIONSHIPS

The phase-relationships in terms of mass-volume and weight-volume for a soil mass are shown by a block diagram in the figure below. A block of unit sectional area is considered. The volumes of the different constituents are shown on the right side and the corresponding mass/weights on the right and left sides of the block. The mass/weight of air may be assumed as zero.

A. Volumetric Ratios

There are three volumetric ratios that are very useful in geotechnical engineering and these can be determined directly from the phase diagram below.
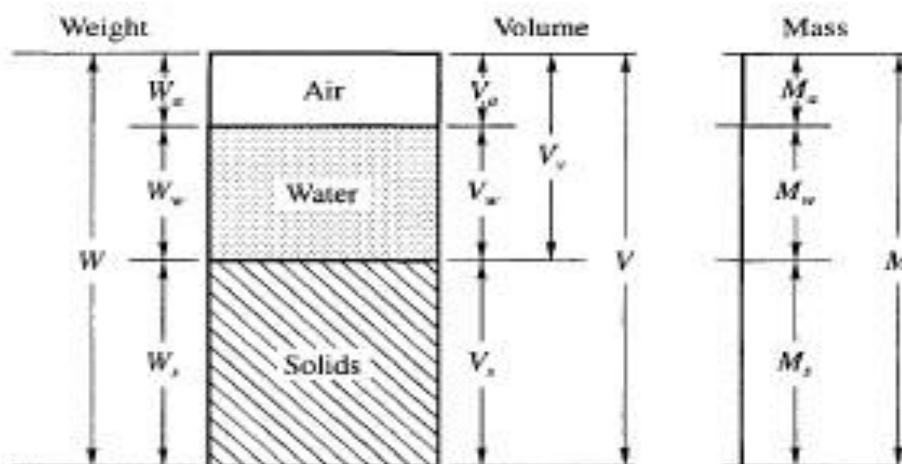

Figure 1. Block diagram – three phases of soil elements.

1. The void ratio, e, is defined as;

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

Where, V_v = volume of voids, and V_s = volume of the solids.

The void ratio e is always expressed as a decimal.

2. The porosity n is defined as;

$$n = \frac{V_v}{\ } \; X\,100\%$$

V

Where, **V** = total volume of the soil sample.

The porosity n is always expressed as a percentage.

3. The degree of saturation S is defined as;

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

Where, V_w = volume of water

It is always expressed as a percentage. When S = 0%, the soil is completely dry, and when S = 100%, the soil is fully saturated.

B. Mass-Volume Relationships

The other aspects of the phase diagram connected with mass or weight also can be explained as:

1. Water Content, w

The water content, w, of a soil mass is defined as the ratio of the mass of water, Mw, in the voids to the mass of solids, Ms, as

$$w = \frac{M_w}{M_s} \times 100$$

The water content, which is usually expressed as a percentage, can range from zero (dry soil) to several hundred percent. The natural water content for most soils is well under 100%, but for the soils of volcanic origin (for example bentonite) it can range up to 500% or more.

2. Density

Another very useful concept is density (or, unit weight) which is expressed as mass per unit volume. There are several commonly used densities. These may be defined as the total (or bulk), or moist density, the dry density, the saturated density, the density of the particles, solid density, and density of water. Each of these densities is defined as follows:

a) Total density,

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

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

b) Dry density

$$\rho_d = \frac{M_s}{V}$$

c) Saturated density

$$\rho_{sat} = \frac{M}{V}$$

d) Density of Solids

$$\rho_s = \frac{M_s}{V_s}$$

e) Density of water

$$\rho_w = \frac{M_w}{V_w}$$

3. Specific Gravity

The specific gravity of a substance is defined as the ratio of its mass in air to the mass of an equal volume of water at reference temperature, 4 °C. The specific gravity of a mass of soil (including air, water and solids) is termed as bulk specific gravity Gm.

It is expressed as:

$$G_m = \frac{\rho_t}{\rho_w} = \frac{M}{V \rho_w}$$

The specific gravity of solids, Gs, (excluding air and water) is expressed as:

$$G_s = \frac{\rho_s}{\rho_w} = \frac{M_s}{V_s \rho_w}$$

C. Interrelationships of Different Parameters

We can establish relationships between the different parameters defined by equations from the equations above. In order to develop the relationships, the block diagram Fig.2 is made use of. Since the sectional area perpendicular to the plane of the paper is assumed as unity, the heights of the blocks will represent the volumes. The volume of solids may be represented as Vs = 1(an assumption). Also when the soil is fully saturated, the voids are completely filled with water.
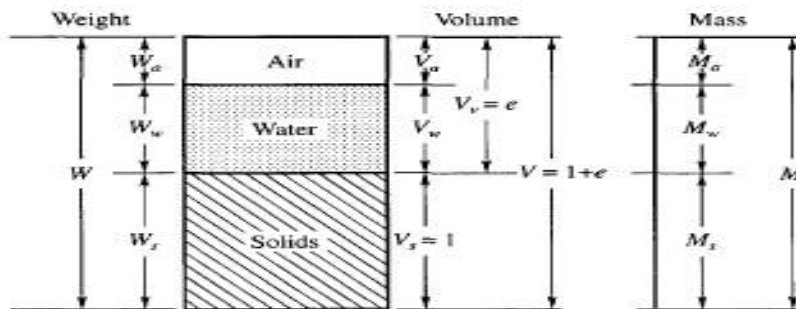

Figure 2

1. Relationship Between e and n (from Fig. 2)

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

$$\text{or } e = \frac{n}{1-n}$$

2. Relationship Between e, Gs and S

Case 1: When partially saturated (S < 100%)

$$S = \frac{V_w}{V_v} = \frac{V_w}{e}; \text{ but } V_w = \frac{M_w}{\rho_w} = \frac{wM_s}{\rho_w} = \frac{wG_sV_s\rho_w}{\rho_w} = wG_s$$

Therefore,

$$S = \frac{wG_s}{e} \text{ or } e = \frac{wG_s}{S}$$

Case 2: When saturated (S = 100%)
From the above equation we have (for S=1)

$$e = wG_s$$

3. Relationships Between Density p and Other Parameters

The density of soil can be expressed in terms of other parameters for cases of soil (1) partially saturated (S < 100%); (2) fully saturated (S = 100%); and (3) Fully dry (S = 0)

Case 1: For S < 100%

$$\rho_t = \frac{M}{V} = \frac{M_s(1+w)}{1+e} = \frac{G_s\rho_w(1+w)}{1+e}$$

From w = eS/Gs; substituting for w in the above equation we have

$$\rho_t = \frac{\rho_w(G_s + eS)}{1+e}$$

Case 2: For S= 100%
S=1, hence

$$\rho_t = \rho_{sat} = \frac{\rho_w(G_s + e)}{1+e}$$

Case 3: For S = 0%
S=0, hence

$$\rho_t = \rho_d = \frac{\rho_w G_s}{1+e}$$

4. Relative Density

The looseness or denseness of sandy soils can be expressed numerically by relative density Dr, defined by the equation:

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100$$

Where e_{max}= void ratio of sand in its loosest state having a dry density of p_{dM} e_{min} = void ratio its densest state having a dry density of p_{dm} e = void ratio under in-situ condition having a dry density of p_d

Now substituting the corresponding dry densities for e_{max}, e_{min} and e in the Equation and simplifying, we have

$$D_r = \frac{\rho_{dM}}{\rho_d} \times \frac{\rho_d - \rho_{dm}}{\rho_{dM} - \rho_{dm}} \times 100$$

The loosest state for a granular material can usually be created by allowing the dry material to fall into a container from a funnel held in such a way that the free fall is about one centimeter. The densest state can be established by a combination of static pressure and vibration of soil packed in a container.

5. Weight-volume relationships

The weight-volume relationships can be established from the earlier equations by substituting for *p* and *W* for *M.* The various equations are tabulated below.

1.   Water $w = \frac{W_w}{W_s} \times 100$ content:

2.   Total $\gamma_t = \frac{W}{V}$ unit weight:

3.   Dry $\gamma_d = \frac{W_s}{V}$ unit weight:

4.   Saturated $\gamma_{sat} = \dfrac{W}{V}$ unit weight:

5.   Unit weight of $\gamma_s = \dfrac{W_s}{V_s}$ solids:

6.   Unit weight of $\gamma_w = \dfrac{W_w}{V_w}$ water :

7.   Mass specific $G_m = \dfrac{W}{V\gamma_w}$ gravity:

8.   Specific $G_s = \dfrac{W_s}{V_s\gamma_w}$ gravity of solids:

9.   Saturated $\gamma_{sat} = \dfrac{\gamma_w(G_s + e)}{1+e}$ unit weight:

10.   Dry   unit $\gamma_d = \dfrac{\gamma_w G_s}{1+e}$ weight:

1.4.2 Laboratory measurements:

It is important to quantify the state of a soil immediately it is received in the testing laboratory and just prior to commencing other tests (e.g. shear tests, compression tests, etc.).

The water content and unit weight are particularly important, since these could change during transportation and storage.

Some physical state properties are calculated following the practical measurement of others; e.g. void ratio from porosity, dry unit weight from unit weight & water content.

1) Water content

The most usual method of determining the water content of soil is to weigh a small representative specimen, drying it to constant weight and then weighing it again. Drying can be carried out using an electric oven set at 104-105° Celsius or using a microwave oven.

Example: A sample of soil was placed in a tin container and weighed, after which it was dried in an oven and then weighed again. Calculate the water content of the soil.

Weight of tin empty	= 16.16 g
Weight of tin + moist soil	= 37.82 g
Weight of tin + dry soil	= 34.68 g
Water content, **w**	= (mass of water) / (mass of dry soil)
w= (37.82 - 34.68) / (34.68 - 16.16)	
w= 0.169	
Percentage water content	= 16.9 %

2) Unit weight

Clay soils: Specimens are usually prepared in the form of regular geometric shapes, (e.g. prisms, cylinders) of which the volume is easily computed. **Sands and gravels**: Specimens have to be placed in a container to determine volume (e.g. a cylindrical can).

Example A soil specimen had a volume of 89.13 ml, a mass before drying of 174.45 g and after drying of 158.73 g; the water content was 9.9 %. Determine the bulk and dry densities and unit weights.

Bulk density r , = (mass of specimen) / (volume of specimen)
= 174.45 / 89.13 g/ml
= 1.957 Mg/m³ [1 g/ml = 1 Mg/m³]
Unit weight   = 9.81m/s² x r Mg/m³
= 19.20 kN/m³

Dry density r_d

= (mass after drying) / (volume)
= 158.73 / 89.13
= 1.781 Mg/m³
Alternatively r_d = r / (1 + w)
= 1.957 / (1+0.099)
= 1.781 Mg/m³
Dry unit weight
g_d = g / (1 + w)
= 19.20 / (1+0.099)
= 17.47 kN/m³

1.4.4 Field measurements

Measurements taken in the field are mostly to determine density/unit weight. The most common application is the determination of the density of rolled and compacted fill, e.g. in road bases, embankments, etc.

Note: You should understand the general principle that density is calculated from the mass and volume of a sample. How a sample of known volume is obtained depends on the nature of the soil.

1. The core cutter method

This method is suitable for soft fine grained soils.

A steel cylinder is driven into the ground, dug out and the soil shaved off level. The mass of soil is found by weighing and deducting the mass of the cylinder. Small samples are taken from both ends and the water content determined.

2. The sand-pouring cylinder method

This method is suitable for stony soils

Using a special tray with a hole in the centre, a hole is formed in the soil and the mass of soil removed is weighed.

The volume of the hole is calculated from the mass of clean dry running sand required to fill the hole.

The sand-pouring cylinder is used to fill the hole in a controlled manner. The mass of sand required to fill the hole is equal to the difference in the weight of the cylinder before and after filling the hole, less an allowance for the sand left in the cone above the hole.
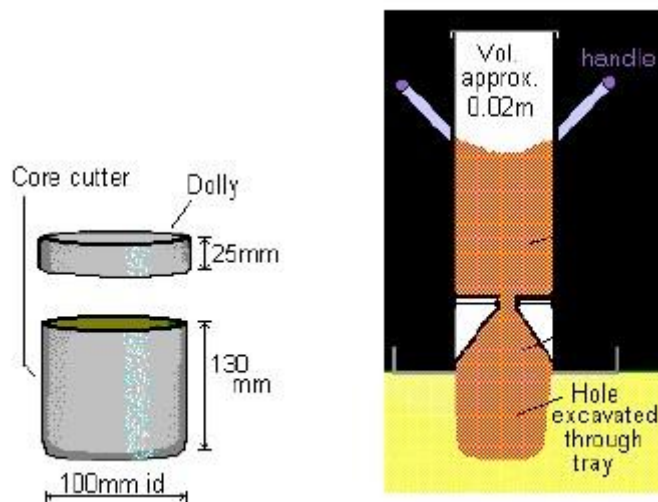
*Reading Assignment: Research on the various field and laboratory tests carried out on soil and the purpose of these tests. Your scope of study should include particle size analysis, sieve analysis, grading curves used, measurement of specific gravity, determination of liquid limit (Casangrande method), determination of the plastic limit and plasticity index of soil.