Lecture 1

SECTION 1

- Soil Formation
- Particle Size Distribution
- Soil Classification

SECTION 2

- Soil Composition
  - 3-phase material
  - Soil Characterization (particle size, soil plasticity)
Soil Mechanics

- Soil mechanics is the branch of science that deals with the study of physical properties of soil and the behavior of soil masses subjected to various types of forces.
  - Classify soils and rocks
  - Establish engineering properties
  - Ascertain the compressibility
  - Ascertain the shear strength

According to Terzaghi (1948):

“Soil Mechanics is the application of laws of mechanics and hydraulics to engineering problems dealing with sediments and other unconsolidated accumulations of solid particles produced by the mechanical and chemical disintegration of rocks regardless of whether or not they contain an admixture of organic constituent.”
Soil Formation

Parent Rock

Residual soil
~ in situ weathering (by physical & chemical agents) of parent rock

Transported soil
~ weathered and transported far away by wind, water and ice.

Soil Formation
~ formed by one of these **three** different processes

- **igneous**
  - formed by cooling of molten magma (lava)
  - e.g., granite

- **sedimentary**
  - formed by gradual deposition, and in layers
  - e.g., limestone, shale

- **metamorphic**
  - formed by alteration of igneous & sedimentary rocks by pressure/temperature
  - e.g., marble
Determination of Particle Size Distribution

- Mechanical analysis is used in the determination of the size range of particles present in a soil, expressed as a percentage of the total dry weight.

- There are two methods that generally utilized to determine the particle size distribution of soil:
  - Sieve Analysis (for particle sizes > 0.075mm in diameter)
  - Hydrometer Analysis (" " < 0.075mm " " )

Particle Size Distributions and Soil Particle Characteristics

- Particle size distribution curve is a representation in graphical or tabular form of the various (diameter) grain sizes in a soil, determined through sieving and sedimentation.

- The particle diameters are plotted in log scale, and the corresponding percent finer in arithmetic scale.
Sieve Analysis

- It is performed by shaking the soil sample through a set of sieves having progressively smaller openings.

Particle Size Distribution Curve
Hydrometer Analysis

- It is based on the principle of sedimentation of soil grains in water.

Also called Sedimentation Analysis

Stoke’s Law

\[ v = \frac{D^2 \gamma_w (G_s - G_L)}{18 \eta} \]
Some commonly used measures are:

a) **Effective size**: $(D_{10})$
   It is the diameter in the particle size distribution curve corresponding to 10% finer. (maximum size of the smallest 10% of the soil)

b) **Uniformity Coefficient**: $C_u = D_{60}/D_{10}$
   It is the ratio of the maximum diameter of the smallest 60% to the effective size.
   - A well graded soil will have $C_u > 4$ for gravels
   - $C_u > 6$ for sands

c) **Coefficient of Curvature**: $C_c = (D_{30})^2 / (D_{60} * D_{10})$
   $D_{30}$: Diameter corresponding the 30% finer

d) **Clay Fraction**: (CF)
   It is the percentage by dry mass of particles smaller than 0.002mm (2μm), and is an index property frequently quoted relation to fine grained soils (soils with 50% or more finer than 63μm). It has a strong influence on the engineering properties of fine grained soils.
Definitions

e) **Well-Graded Material** – Contains particles of a *wide range of sizes*. The smaller particles fill the spaces left between the larger particles; therefore the soil has greater strength than a poorly graded soil, and lower permeability.

f) **Poorly – Graded Material** – Contains a large portion of *uniformly sized particles*. This particular soil has larger voids in its structure and poor strength along with high permeability.
Soil Plasticity & Consistency Limits

- In the early 1900s a Swedish scientist “Atterberg” developed a method to describe the consistency of fine grained soils with varying degree of moisture content.

- If a soil is gradually dried from a slurry, it passes from state of viscous liquid to a plastic state; then to a semi-solid, and finally into a solid state. The moisture contents at which the soil passes from one state to the next are known as consistency limits (also called “Atterberg Limits”)

- Consistency limits are utilized to compare soils from different locations and different depths.

- There are 4 basic states

Atterberg Limits

- Consistency of fine-grained soil varies in proportion to the water content

By P. Jayawickrama, Texas Tech University
Definitions

a) **Liquid Limit (LL)**: is the minimum moisture content at which the soil will flow under its own weight. The moisture content (in %) required to close a distance of 12.7mm along the bottom of the groove after 25 blows is the liquid limit.

b) **Plastic Limit (PL)**: is the moisture content (in %) at which the soil when rolled into threads of 3.2mm in diameter, crumbles. PL is the lower limit of the plastic stage of the soil. The test is simple and performed by repeated rollings of ellipsoidal size soil mass by hand on a ground glass plate.

c) **Shrinkage Limit (SL)**: is the moisture content (in %) at which the volume change of the soil mass ceases.
Definitions

d) **Plasticity Index (PI):** is a measure of the range of the moisture contents over which a soil is plastic.

\[
PI = LL - PL
\]

e) **Liquidity Index (LI):** The relative consistency of a cohesive soil in a natural state can be defined by the ratio called LI.

\[
LI = \frac{w_{PL}}{LL - PL}
\]

f) **Activity:** is the ratio of PI to the clay fraction (% by dry weight of particles < 2μm)

\[
A = \frac{PI}{\text{Clay fraction\%}}
\]

CLASSIFICATION OF SOILS

- The sizes of particles that make up soil may vary widely depending on the predominant size of particles. Soils are classified as:
  1) Gravel
  2) Sand
  3) Silt
  4) Clay

- The most comprehensive is the Unified Soil Classification System (USCS).
This system classifies soils under two broad categories:

- **Coarse Grained Soils**: are gravelly and sandy in nature with <50% passing through a #200 sieve (diameter=0.075mm)
  - G: “Gravel”
  - S: “Sand”

- **Fine Grained Soils**: have 50% or more passing through the #200 sieve.
  - M: inorganic Silt
  - O: Organic Silts and Clays
  - C: inorganic Clay
  - Pt: Peat, muck, highly organic soils

The standard system used worldwide for most major construction projects is known as the Unified Soil Classification System (USCS).

This is based on an original system devised by Cassagrande. Soils are identified by symbols determined from:

- Sieve analysis and
- Atterberg Limit tests.
USCS Table

Classification Procedure

- **Coarse Grained Materials**
  - If more than half of the material is coarser than the 75 μm sieve, the soil is classified as coarse. The following steps are then followed to determine the appropriate 2 letter symbol
  - **Determine the 1st letter of the symbol**
    - If more than half of the coarse fraction is sand then use prefix S
    - If more than half of the coarse fraction is gravel then use prefix G
  - **Determine the 2nd letter of symbol**
    - This depends on the uniformity coefficient Cu and the coefficient of curvature Cc obtained from the grading curve, on the percentage of fines, and the type of fines.
Classification Procedure

- First determine the percentage of fines, that is the % of material passing the 75 μm sieve.
- Then if % fines is
  - < 5% use W or P as suffix
  - > 12% use M or C as suffix
  - between 5% and 12% use dual symbols. Use the prefix from above with first one of W or P and then with one of M or C.
  - If W or P are required for the suffix then Cu and Cc must be evaluated

- If prefix is G then suffix is W if Cu > 4 and Cc is between 1 & 3
  otherwise use P
- If prefix is S then suffix is W if Cu > 6 and Cc is between 1 & 3
  otherwise use P

Classification Procedure

- If M or C are required they have to be determined from the procedure used for fine grained materials discussed below. Note that M stands for Silt and C for Clay. This is determined from whether the soil lies above or below the A-line in the plasticity chart.

- For a coarse grained soil which is predominantly sand the following symbols are possible

  - SW, SP, SM, SC
  - SW-SM, SW-SC, SP-SM, SP-SC
Classification Procedure

- These are classified solely according to the results from the Atterberg Limit Tests. Values of the Plasticity Index and Liquid Limit are used to determine a point in the plasticity chart. The classification symbol is determined from the region of the chart in which the point lies.

Examples
- CH: High plasticity clay
- CL: Low plasticity clay
- MH: High plasticity silt
- ML: Low plasticity silt
- OH: High plasticity organic soil (Rare)
- Pt: Peat

Casagrande Plasticity Chart

Comparing soils at equal liquid limit
toughness and dry strength increase
with increasing plasticity index
3-Phase Material

Water

Air

Solid

The Mineral Skeleton

Solid Particles

Voids (air or water)

Volume
Three Phase Diagram

Mineral Skeleton

Idealization: Three Phase Diagram

Air
Water
Solid

Fully Saturated Soils

Mineral Skeleton

Fully Saturated

Water
Solid
Dry Soils

- Mineral Skeleton
- Solid
- Air
- Dry Soil

Partly Saturated Soils

- Mineral Skeleton
- Solid
- Water
- Air
- Partly Saturated Soils
Objectives of a Phase Diagram

To compute the weights (or masses) and volumes of the three different phases.

Notation

- $M$ = mass or weight
- $V$ = volume
- $s$ = soil grains
- $w$ = water
- $a$ = air
- $v$ = voids
- $t$ = total

Phase Diagram
Volume Relationships

**Void ratio (e):** is a measure of the void volume.

\[ e = \frac{V_V}{V_S} \]

**Porosity (n):** is also a measure of the void volume, expressed as a percentage.

\[ n = \frac{V_V}{V_T} \times 100\% \]

Theoretical range: 0 - 100%
### Volume Relationships

**Degree of saturation (S):** is the percentage of the void volume filled by water.

\[ S = \frac{V_W}{V_V} \times 100\% \]

Range: 0 - 100%

- **Dry**
- **Saturated**

### Weight Relationships

**Water content (w):** is a measure of the water present in the soil.

\[ W = \frac{W_w}{W_s} \times 100\% \]

Expressed as percentage.

Range = 0 – 100%.
Unit Weight Relationships

**Natural Unit Weight** ($\gamma$): is the density of the soil in the current state.

$$\gamma = \frac{W}{V}$$

**Dry Unit Weight** ($\gamma_d$): is the unit weight of the soil in dry state.

$$\gamma_d = \frac{W_s}{V}$$

**Saturated Unit Weight** ($\gamma_{sat}$): is the unit weight of the soil when the voids are filled with water.

$$\gamma_{sat} = \frac{W_s + V_v \cdot \gamma_w}{V}$$

**Submerged Unit Weight** ($\gamma_{sub}$): is the effective unit weight of the soil when it is submerged.

$$\gamma_{sub} = \gamma_{sat} - \gamma_w$$
Phase Relations

Consider a fraction of the soil where $V_s = 1$.

The other volumes can be obtained from the previous definitions.

The weights can be obtained from:

Weights = Unit Weights $\times$ Volume

Phase Relations

From the previous definitions,

$$w = \frac{W_w}{W_s} = \frac{Se}{G_s}$$

$$n = \frac{V_V}{V_T} = \frac{e}{1+e}$$
### Phase Relations

\[ \gamma = \frac{W_T}{V_T} = \frac{G_S + Se}{1 + e} \gamma_W \]

\[ \gamma_{sat} = \frac{W_T}{V_T} = \frac{G_S + e}{1 + e} \gamma_W \]

\[ \gamma_d = \frac{W_S}{V_T} = \frac{G_S}{1 + e} \gamma_W \]

### Definitions

Bulk (natural), saturated, dry and submerged densities \((\rho)\) are defined in a similar manner.

Here, you can also use mass (kg) instead of weight (kN).

\[ \gamma / g = \rho = \frac{M}{V} \]

\(\text{N/m}^3\) \(\text{m/s}^2\) \(\text{kg/m}^3\)
Specific Gravity

\[ G_s = \frac{\text{Weight of a Substance}}{\text{Weight of an Equal Volume of Water}} \]

\[ G_s = \frac{\text{Unit Weight of a Substance}}{\text{Unit Weight of Water}} \]

- Unit weight of Water, \( \gamma_w \)
  - \( \gamma_w = 1.0 \text{ g/cm}^3 \) (strictly accurate at 4° C)
  - \( \gamma_w = 9.81 \text{ kN/m}^3 \)

In Terms of Density

i. Density of water : \( \rho_w = 1000\text{kg/m}^3 \)

ii. Dry density of soil : \( \rho_d = \frac{M_s}{V_T} = \frac{G_s}{1 + e} \rho_w \)

iii. Bulk density of unsaturated or saturated soil: \( \rho = \frac{M_T}{V_T} = \frac{G_s + Se}{1 + e} \rho_w \)

iv. Air content (A) : \( A = \frac{V_a}{V_T} = \frac{e - G_s W}{1 + e} \)
Relationship between parameters

- These definitions can be used to determine any desired relationships between above quantities, and hence to determine void ratio, degree of saturation, etc. That cannot be measured directly by laboratory tests. Some relationships are as follows:

For unsaturated soils:

\[
\frac{w}{W_s} = \frac{S_e}{G_s} \quad e = \frac{G_s w}{S} \tag{1}
\]

For saturated soils: \( S = 1 \) then; \( e = G_s w \)

- Bulk density: \( \rho = \frac{M_s}{V_T} = \frac{G_s + S_e}{1 + e} \rho_w \)\( \quad \rho = \frac{(G_s w + S_s)}{1 + e} \rho_n = \frac{G_s (w + 1) \rho_n}{1 + e} \)

- Dry density: \( \rho_d = \frac{M_s}{V_T} = \frac{G_s}{1 + e} \rho_w \)\( \quad \rho_d (1 + w) = \rho \)

- Degree of Saturation:

\[
S = \frac{G_s w \rho}{(1 + w) G_s \rho_n - \rho}
\]
Try not to *memorize* the equations. *Understand* the definitions, and develop the relations from the phase diagram with $V_S = 1$;

- Assume $G_S$ (2.6-2.8) when not given;
- Do not mix densities and unit weights;
- Soil grains are incompressible. Their mass and volume remain the same at any void ratio.