KIIT POLYTECHNIC

LEARNING MATERIALS
ON

GEOTECHNICAL ENGINEERING

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CHAPTER 1:

INTRODUCTION

1.1 Introduction to Geotechnical Engineering

Geotechnical Engineering is a branch of civil engineering that deals with the behaviour of earth materials. It uses principles of soil mechanics and rock mechanics to investigate subsurface conditions and materials; determine the relevant physical/mechanical and chemical properties of these materials; evaluate stability of natural slopes and man-made soil deposits; assess risks posed by site conditions; design earthworks and foundation structures; and monitor site conditions, earthwork and foundation construction.

Key Components of Geotechnical Engineering:

1. **Soil Mechanics**: The study of soil behaviour under different loading conditions.
2. **Rock Mechanics**: The study of rock behaviour in the field of engineering.
3. **Foundation Engineering**: The design and construction of foundation systems.
4. **Earth Retaining Structures**: Design of walls and systems that hold back soil.
5. **Slope Stability**: Analysis and design of natural and man-made slopes.
6. **Ground Improvement**: Techniques to improve the engineering properties of soil.

Importance in Civil Engineering Projects:

Geotechnical engineering is crucial in most construction projects as it provides essential information about:

- The suitability of the soil for supporting structures
- Potential settlement issues
- Stability concerns for excavations and slopes
- Required foundation types and depths
- Groundwater conditions
- Soil improvement techniques when needed

1.2 Soil and Soil Engineering

Definition of Soil

From a geological perspective, soil is the naturally occurring, unconsolidated or loosely compacted material covering the earth's surface, created through weathering processes.

From an engineering perspective, soil is defined as an unconsolidated aggregate of mineral particles and decayed organic matter (solid particles) with liquid and gas in the empty spaces between the solid particles.

Components of Soil:

1. **Solid Phase**: Mineral particles of varying sizes (clay, silt, sand, gravel)
2. **Liquid Phase**: Usually water
3. **Gaseous Phase**: Air or other gases

Soil Engineering:

Soil engineering, also known as geotechnical engineering, involves:

1. **Site Investigation**: Determining subsurface conditions through field exploration and laboratory testing.
2. **Soil Analysis**: Evaluating soil properties relevant to construction.
3. **Design Solutions**: Creating appropriate foundation and earthwork designs based on soil conditions.
4. **Construction Monitoring**: Ensuring that construction meets design specifications.
5. **Remediation**: Addressing problematic soil conditions through various improvement techniques.

1.3 Scope of Soil Mechanics

Soil mechanics is the application of laws of mechanics and hydraulics to engineering problems dealing with soil as an engineering material. The scope of soil mechanics includes:

1. Classification and Identification of Soils

- Grain size distribution
- Consistency limits (Atterberg limits)
- Classification systems (IS, USCS, AASHTO)

2. Physical Properties of Soils

- Density relationships
- Water content
- Specific gravity
- Void ratio
- Porosity
- Degree of saturation

3. Mechanical Properties of Soils

- Shear strength

- Compressibility
- Permeability
- Consolidation characteristics

4. Practical Applications

- Foundation design
- Earth pressure calculations for retaining structures
- Slope stability analysis
- Settlement predictions
- Bearing capacity determinations
- Ground improvement techniques
- Embankment and dam design
- Excavation support systems

5. Special Problem Areas

- Expansive soils
- Collapsible soils
- Liquefaction potential
- Frost action in soils
- Erosion control

1.4 Origin and Formation of Soil

Soil formation is a complex and continuous process involving the breakdown of parent material through physical, chemical, and biological processes.

Parent Materials:

- **Igneous Rocks**: Formed from cooling of molten magma (e.g., granite, basalt)
- **Sedimentary Rocks**: Formed from deposition and consolidation of sediments (e.g., limestone, sandstone)
- **Metamorphic Rocks**: Formed from transformation of existing rocks under heat and pressure (e.g., marble, slate)

Weathering Processes:

1. Physical Weathering

- **Freeze-Thaw Action**: Water expands upon freezing, creating pressure in rock cracks
- **Temperature Changes**: Differential expansion and contraction causes rock fracturing
- **Root Action**: Plant roots grow into cracks, widening them
- **Exfoliation**: Outer layers of rock peel away due to pressure release
- **Abrasion**: Particles carried by wind, water, or ice erode rock surfaces

2. Chemical Weathering

- **Oxidation**: Reaction with oxygen (e.g., iron rusting)
- **Hydrolysis**: Reaction with water (e.g., feldspar to clay)
- **Carbonation**: Reaction with carbonic acid from rainwater and CO_2
- **Solution**: Dissolution of minerals in water
- **Hydration**: Absorption of water into mineral structure

3. Biological Weathering

- Action of organisms (plants, animals, bacteria, fungi)
- Production of organic acids
- Physical breakdown through burrowing and root growth

Transportation and Deposition:

After weathering, soil materials may be transported by:

- **Water**: Rivers, streams, floods (alluvial deposits)
- **Wind**: Aeolian deposits
- **Gravity**: Colluvial deposits
- **Ice**: Glacial deposits
- **In-situ weathering**: Residual soils

Types of Soils Based on Origin:

1. **Residual Soils**: Formed in-place from weathering of bedrock
2. **Transported Soils**:
   - **Alluvial**: Deposited by running water
   - **Lacustrine**: Deposited in lake beds
   - **Marine**: Deposited in oceans
   - **Glacial**: Deposited by glaciers
   - **Aeolian**: Deposited by wind
   - **Colluvial**: Moved by gravity

Engineering Significance:

The origin and formation of soil significantly influence its engineering properties:

- Residual soils often retain some structure of the parent rock
- Transported soils tend to be sorted by particle size
- Glacial deposits are typically heterogeneous and may contain large boulders
- Aeolian deposits are often uniform in particle size
- Marine clays may be sensitive to disturbance

Understanding soil formation helps engineers predict soil behavior and design accordingly.

CHAPTER 2:

SOIL AS A THREE-PHASE SYSTEM

2.1 Introduction to Three-Phase System

Soil is a three-phase system consisting of solid particles, water, and air. This concept is fundamental to understanding soil behaviour in geotechnical engineering.

The Three Phases:

1. **Solid Phase**: Mineral particles of different sizes and shapes that form the soil skeleton.
2. **Liquid Phase**: Usually water, which occupies some or all of the voids between solid particles.
3. **Gaseous Phase**: Air or other gases that occupy the remaining voids not filled with water.

Representation of the Three-Phase System:

Soil can be represented diagrammatically as three blocks showing the volumetric and weight relationships between the three phases:

```
┌─────────────────┐
│        │
│  Air     │ ─┐
│ (weight   │  │
│ negligible)│  │
│        │ │
├─────────────────┤ │ Volume of voids (Vv)
│        │ │
│  Water   │  │
│ (weight   │ ─┘
```

```
│   = Ww)   │
│         │
├─────────────────┤
│         │
│  Solids  │ ─┐
│ (weight  │ │ Volume of solids (Vs)
│   = Ws)  │ │
│         │ ─┘
└─────────────────┘

Total volume (V)
Total weight (W = Ws + Ww)
```

Engineering Implications:

The three-phase nature of soil affects all its engineering properties:

- Strength depends on interaction between particles and water
- Compressibility relates to how these phases change in volume under load
- Permeability depends on the interconnectedness of the voids
- Stability issues occur when phase relationships change (e.g., during saturation)

Understanding the three-phase system is essential for analyzing soil behavior, particularly during loading, drainage, and environmental changes.

2.2 Water Content, Density, Specific Gravity

Water Content (w)

Water content is the ratio of the weight of water to the weight of solid particles in a soil mass, expressed as a percentage:

$w = (W_w/W_s) \times 100\%$

Where:

- w = water content (%)
- W_w = weight of water
- W_s = weight of solid particles

Practical Range:

- Sands and gravels: 0-15%
- Silts: 5-30%
- Clays: 10-50% (can exceed 100% for some highly plastic clays)

Laboratory Determination:

1. Weigh wet soil sample (Wt)
2. Dry sample in oven at 105-110°C for 24 hours
3. Weigh dried sample (Ws)
4. Calculate water content: $w = [(W_t - W_s)/W_s] \times 100\%$

Density

Density refers to the mass per unit volume. In soil mechanics, we consider several types of density:

1. Bulk Density (ρ)

The total mass of soil (solids + water) per unit volume:

$\rho = W/V$

Where:

- ρ = bulk density (g/cm³ or kg/m³)
- W = total weight of soil
- V = total volume of soil

2. Dry Density (ρd)

The mass of solid particles per unit total volume:

$\rho_d = W_s/V$

or in terms of bulk density and water content:

$\rho_d = \rho/(1+w)$

Where:

- ρ_d = dry density
- W_s = weight of solid particles
- V = total volume
- w = water content (as a decimal)

Specific Gravity (Gs)

Specific gravity is the ratio of the unit weight of soil solids to the unit weight of water at 4°C:

$G_s = \rho_s/\rho_w$

Where:

- G_s = specific gravity of soil solids

- ρ_s = density of soil solids
- ρ_w = density of water (1 g/cm³ at 4°C)

Typical Values:

- Quartz and most silicate minerals: 2.65-2.67
- Clay minerals: 2.70-2.80
- Soils with organic content: 2.0-2.5
- Most inorganic soils: 2.60-2.80

Significance:

- Essential for phase relationship calculations
- Indicator of mineral composition
- Used in hydrometer analysis for grain size distribution

2.3 Voids Ratio and Porosity

Voids Ratio (e)

Voids ratio (also called void ratio) is the ratio of the volume of voids to the volume of solids in a soil mass:

$e = V_v/V_s$

Where:

- e = voids ratio
- V_v = volume of voids (air + water)
- V_s = volume of solid particles

Typical Values:

- Dense sands: 0.3-0.5
- Loose sands: 0.5-0.8
- Soft clays: 0.9-1.4
- Organic clays: 2.5-3.5

Engineering Significance:

- Indicates the potential for settlement (higher e = more potential for compression)
- Relates to soil density state
- Influences permeability and strength
- Used in settlement calculations

Porosity (n)

Porosity is the ratio of the volume of voids to the total volume of the soil mass, expressed as a percentage:

$n = (V_v/V) \times 100\%$

Where:

- n = porosity (%)
- V_v = volume of voids
- V = total volume

Relationship with Voids Ratio:

The relationship between porosity and voids ratio is:

$n = e/(1+e)$ or $e = n/(1-n)$

Typical Values:

- Dense sands: 23-30%
- Loose sands: 30-45%
- Soft clays: 45-55%
- Organic soils: >65%

Engineering Significance:

- Indicates the proportion of space available for fluid flow
- Relates to soil compactness
- Influences soil behavior under loading
- Important for groundwater studies

2.4 Percentage of Air Voids and Air Content

Percentage of Air Voids (na)

The air voids percentage is the ratio of the volume of air to the total volume of the soil mass, expressed as a percentage:

$n_a = (V_a/V) \times 100\%$

Where:

- n_a = percentage of air voids (%)
- V_a = volume of air
- V = total volume

Air Content (ac)

Air content is the ratio of the volume of air to the volume of voids:

ac = Va/Vv

Where:

- ac = air content
- Va = volume of air
- Vv = volume of voids

Relationship with Degree of Saturation:

Air content and degree of saturation (S) are related:

ac = 1 - S

Where S is the degree of saturation (as a decimal).

Engineering Significance:

1. **Compaction Control**:
   - In compacted fills, air voids should typically be kept below 5-10%
   - Higher air voids can lead to future settlement
2. **Frost Susceptibility**:
   - Soils with high air content may be more susceptible to frost damage
   - Air voids provide space for ice formation and expansion
3. **Collapse Potential**:
   - Soils with high air content may be susceptible to collapse upon wetting
   - Critical for evaluating loess and other potentially collapsible soils
4. **Strength Considerations**:
   - Higher air content generally means lower strength
   - Critical for temporary works design
5. **Permeability**:
   - Higher air content usually means higher permeability
   - Affects drainage characteristics

2.7 Interrelationship of Various Soil Parameters

Understanding the relationships between soil parameters is essential for geotechnical engineering. These relationships allow engineers to determine unknown parameters from known ones.

Key Relationships:

1. Void Ratio (e) and Porosity (n)

e = n/(1-n)
n = e/(1+e)

2. Degree of Saturation (S), Water Content (w), Void Ratio (e), and Specific Gravity (Gs)

$S = w \times G_s/e$

$w = S \times e/G_s$

3. Bulk Density (ρ), Dry Density (ρd), and Water Content (w)

$\rho = \rho_d \times (1+w)$

$\rho_d = \rho/(1+w)$

4. Void Ratio (e), Specific Gravity (Gs), and Dry Density (ρd)

$e = (G_s \times \rho_w/\rho_d) - 1$

$\rho_d = G_s \times \rho_w/(1+e)$

5. Saturated Density (ρsat), Dry Density (ρd), and Void Ratio (e)

$\rho_{sat} = \rho_d + (e \times \rho_w)$

$\rho_{sat} = \rho_w \times (G_s + e)/(1+e)$

6. Submerged Density (ρ'), Specific Gravity (Gs), and Void Ratio (e)

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

$\rho' = \rho_w \times (G_s-1)/(1+e)$

7. Degree of Saturation (S), Air Content (ac), and Percentage of Air Voids (na)

$S + a_c = 1$

$n_a = n \times (1-S)$

8. Density Index (ID), Void Ratios (e, emax, emin)

$I_D = (e_{max} - e)/(e_{max} - e_{min})$

$e = e_{max} - I_D \times (e_{max} - e_{min})$

Phase Diagram:

The three-phase diagram is a useful visual tool for understanding these relationships:

```
┌──────────────────┐
│   Va     │ ─┐    Va = Volume of air
├──────────────────┤ │   Vw = Volume of water
│   Vw     │ │──── Vv = Volume of voids (Va + Vw)
├──────────────────┤ │
│   Vs     │ ─┘    Vs = Volume of solids
└──────────────────┘

    V        V = Total volume
```

Weight:
Wa (≈0)
Ww
Ws
W = Ww + Ws

Practical Application:

These interrelationships allow engineers to:

1. Calculate unknown parameters when testing is not possible

2. Check the consistency of laboratory test results
3. Estimate soil behavior under different conditions
4. Convert between different ways of expressing soil conditions
5. Predict changes in soil properties due to changes in water content or density

2.8 Numerical Practice on Phase Relationships

Let's work through some practical numerical examples to demonstrate the application of phase relationships in soil mechanics.

Example 1: Basic Phase Relationship Calculations

Given:

- A soil sample has a bulk density of 1.96 g/cm³
- Water content is 18%
- Specific gravity of soil solids is 2.70

Calculate: a) Dry density b) Void ratio c) Porosity d) Degree of saturation

Solution:

a) Dry density: $\rho d = \rho/(1+w) = 1.96/(1+0.18) = 1.66$ g/cm³

b) Void ratio: $e = (Gs \times \rho w/\rho d) - 1 = (2.70 \times 1.0/1.66) - 1 = 0.627$

c) Porosity: $n = e/(1+e) = 0.627/(1+0.627) = 0.385$ or 38.5%

d) Degree of saturation: $S = w \times Gs/e = 0.18 \times 2.70/0.627 = 0.775$ or 77.5%

Example 2: Compaction Specifications

Given:

- A sandy soil has a maximum void ratio (emax) of 0.92
- The minimum void ratio (emin) is 0.42
- The compaction specification requires a minimum density index of 70%
- Specific gravity of soil solids is 2.65

Calculate: a) The required void ratio b) The corresponding dry density c) If the natural water content is 8%, what should be the minimum field bulk density?

Solution:

a) Required void ratio: ID = (emax - e)/(emax - emin) 0.70 = (0.92 - e)/(0.92 - 0.42) 0.70 × 0.50 = 0.92 - e 0.35 = 0.92 - e e = 0.57

b) Corresponding dry density: $\rho d = Gs \times \rho w/(1+e) = 2.65 \times 1.0/(1+0.57) = 1.69$ g/cm³

c) Minimum field bulk density: $\rho = \rho d \times (1+w) = 1.69 \times (1+0.08) = 1.83$ g/cm³

Example 3: Phase Transition Analysis

Given:

- A clay soil sample has a volume of 500 cm³ and weighs 925 g
- After drying in the oven, it weighs 720 g
- The specific gravity of the soil solids is 2.75

Calculate: a) Water content b) Void ratio c) Porosity d) Degree of saturation e) Volume change if the soil becomes fully saturated without change in void ratio

Solution:

a) Water content: $w = (Ww/Ws) \times 100\% = (925-720)/720 \times 100\% = 28.5\%$

b) Dry density: $\rho d = Ws/V = 720/500 = 1.44$ g/cm³

Void ratio: $e = (Gs \times \rho w/\rho d) - 1 = (2.75 \times 1.0/1.44) - 1 = 0.910$

c) Porosity: $n = e/(1+e) = 0.910/(1+0.910) = 0.476$ or 47.6%

d) Degree of saturation: $S = w \times Gs/e = 0.285 \times 2.75/0.910 = 0.862$ or 86.2%

e) Volume of water at current state: $Vw = Ww/\rho w = (925-720)/1.0 = 205$ cm³

Volume of voids: $Vv = e \times Vs = e \times (Ws/Gs \times \rho w) = 0.910 \times (720/2.75 \times 1.0) = 238$ cm³

Additional water needed for full saturation: $\Delta Vw = Vv - Vw = 238 - 205 = 33$ cm³

This represents the volume change if the soil becomes fully saturated without change in void ratio.

Example 4: Weight-Volume Relationship for a Three-Phase System

Given:

- A soil sample has a total volume of 800 cm³
- The sample weighs 1520 g and has a water content of 15%
- The specific gravity of soil solids is 2.68

Calculate: a) The volumes of solids, water, and air b) The void ratio, porosity, and degree of saturation c) The bulk, dry, and saturated densities

Solution:

a) Weight of solids: $W_s = W/(1+w) = 1520/(1+0.15) = 1321.7$ g

Volume of solids: $V_s = W_s/(G_s \times \rho_w) = 1321.7/(2.68 \times 1.0) = 493.2$ cm³

Weight of water: $W_w = W - W_s = 1520 - 1321.7 =$

Weight of water: $W_w = W - W_s = 1520 - 1321.7 = 198.3$ g

Volume of water: $V_w = W_w/\rho_w = 198.3/1.0 = 198.3$ cm³

Volume of voids: $V_v = V - V_s = 800 - 493.2 = 306.8$ cm³

Volume of air: $V_a = V_v - V_w = 306.8 - 198.3 = 108.5$ cm³

b) Void ratio: $e = V_v/V_s = 306.8/493.2 = 0.622$

Porosity: $n = V_v/V = 306.8/800 = 0.384$ or 38.4%

Degree of saturation: $S = V_w/V_v = 198.3/306.8 = 0.646$ or 64.6%

c) Bulk density: $\rho = W/V = 1520/800 = 1.90$ g/cm³

Dry density: $\rho_d = W_s/V = 1321.7/800 = 1.65$ g/cm³

Saturated density: $\rho_{sat} = (W_s + V_v \times \rho_w)/V = (1321.7 + 306.8 \times 1.0)/800 = 2.04$ g/cm³

CHAPTER 3: INDEX PROPERTIES AND LABORATORY TESTS

3.1 Water Content Measurement Techniques

Water content (moisture content) is one of the most fundamental soil properties. It significantly influences soil behavior and is required for many geotechnical calculations.

Definition:

Water content (w) is the ratio of the weight of water to the weight of solid particles in a soil mass, expressed as a percentage:

$w = (W_w/W_s) \times 100\%$

Standard Oven Drying Method (IS: 2720 Part II)

This is the reference method against which all other methods are calibrated.

Procedure:

1. Take a representative soil sample (typically 25-50g for fine-grained soils, 200-500g for coarse-grained soils)
2. Weigh the container (Wc)
3. Place the soil in the container and weigh (Wcs)
4. Dry in an oven at 105-110°C for 24 hours (or until constant weight is achieved)
5. Remove from oven, allow to cool in a desiccator, and weigh (Wds)
6. Calculate water content: $w = [(W_{cs} - W_{ds})/(W_{ds} - W_c)] \times 100\%$

Advantages:

- High accuracy and reliability
- Considered the standard reference method

Limitations:

- Time-consuming (24 hours)
- Requires laboratory facilities
- Heat-sensitive soils (organic, gypsum-rich) may decompose

Rapid Moisture Meter

A quicker alternative to the oven method, especially useful for field testing.

Principle:

When calcium carbide (CaC_2) reacts with water in soil, acetylene gas is produced. The pressure developed in a closed vessel is proportional to the moisture content.

Procedure:

1. Weigh a specified amount of soil sample
2. Place soil and calcium carbide reagent in the pressure vessel
3. Seal and shake vigorously
4. Read the pressure gauge, which is calibrated to show moisture content directly

Advantages:

- Results available in minutes
- Portable for field use
- Reasonable accuracy for most soils

Limitations:

- Less accurate than oven method
- Requires calibration for different soil types

- Not suitable for highly organic soils

Infrared Moisture Meter

Uses infrared radiation to rapidly heat and dry the soil sample.

Procedure:

1. Weigh sample container
2. Add soil sample and weigh
3. Place in infrared moisture meter
4. The meter heats the sample with infrared radiation
5. The device automatically calculates water content based on weight loss

Advantages:

- Fast (typically 15-30 minutes)
- Easy to use
- Good accuracy for most soils

Limitations:

- Less accurate than oven method for certain soils
- More expensive equipment
- May decompose organic matter

Microwave Oven Method

An expedient method used when quick results are needed.

Procedure:

1. Weigh container
2. Add soil sample and weigh
3. Dry in microwave oven using low to medium power for short intervals (1-2 minutes)
4. Allow to cool and weigh
5. Repeat until constant weight is achieved
6. Calculate water content as in oven method

Advantages:

- Results in 10-15 minutes
- Uses commonly available equipment
- Reasonable accuracy

Limitations:

- Risk of overheating and decomposing soil
- Not standardized
- Potential for non-uniform drying
- Not recommended for soils with organic matter or gypsum

Pycnometer Method

Useful for determining water content of very small samples.

Procedure:

1. Weigh empty pycnometer (W_1)
2. Add soil sample and weigh (W_2)
3. Fill with distilled water to the mark and weigh (W_3)
4. Empty, clean, fill with distilled water only and weigh (W_4)
5. Calculate water content using: $w = [(W_4-W_1)-(W_3-W_2)]/(W_2-W_1) \times 100\%$

Advantages:

- Suitable for very small samples
- Useful for specific research purposes

Limitations:

- Complex procedure
- Greater potential for error
- Time-consuming

3.2 Specific Gravity - Laboratory Determination

Specific gravity (Gs) is the ratio of the mass density of soil solids to the mass density of water at 4°C. It is an important parameter in phase relationship calculations.

Pycnometer Method (IS: 2720 Part III)

This is the standard method for determining specific gravity of soil solids.

Equipment Required:

- Density bottle (pycnometer) with stopper (50 or 100 ml capacity)
- Vacuum pump or aspirator
- Distilled water
- Balance sensitive to 0.001g
- Thermometer
- Desiccator
- Oven

Procedure:

1. Clean and dry the pycnometer, weigh it (W_1)
2. Place about 10g of oven-dried soil in the pycnometer and weigh (W_2)
3. Add distilled water to cover the soil
4. Apply vacuum to remove entrapped air (15-30 minutes)
5. Fill the pycnometer completely with de-aired distilled water and insert stopper
6. Wipe outside dry and weigh (W_3)
7. Empty and clean the pycnometer
8. Fill with distilled water only, insert stopper, wipe dry, and weigh (W_4)
9. Record the temperature of the water

Calculation:

$G_s = (W_2 - W_1)/[(W_4 - W_1) - (W_3 - W_2)]$

Temperature Correction:

Specific gravity at temperature T°C needs to be corrected to 27°C (standard temperature for India):
$G_s(27°C) = G_s(T°C) \times$ [Density of water at T°C / Density of water at 27°C]

Gas Jar Method (for Coarse-Grained Soils)

This method is suitable for soil particles retained on 4.75mm sieve (gravels).

Equipment Required:

- Gas jar of 1000ml capacity
- Balance
- Thermometer
- Distilled water

Procedure:

1. Weigh the clean, dry gas jar (W_1)
2. Place oven-dried soil sample in the jar and weigh (W_2)
3. Add distilled water to the 500ml mark
4. Stir thoroughly to remove entrapped air
5. Fill to 1000ml mark with distilled water and weigh (W_3)
6. Empty the jar, fill with distilled water to 1000ml mark and weigh (W_4)
7. Record the temperature

Calculation:

$G_s = (W_2 - W_1)/[(W_4 - W_1) - (W_3 - W_2)]$

Density Bottle Method (for Fine-Grained Soils)

Similar to the pycnometer method but specifically for fine-grained soils.

Procedure:

Same as pycnometer method, but typically with smaller samples (5-10g) and smaller density bottles.

Typical Values of Specific Gravity:

Soil Type	Specific Gravity Range
Sand (quartz dominant)	2.65-2.67
Silt	2.65-2.70
Clay (kaolinite)	2.60-2.68
Clay (montmorillonite)	2.70-2.80
Organic soils	2.00-2.40
Peat	1.30-1.90

Factors Affecting Specific Gravity Determination:

1. **Entrapped Air**: Affects weight measurements, must be removed through vacuum application
2. **Temperature**: Affects density of water, requires correction
3. **Mineral Composition**: Different minerals have different specific gravities
4. **Presence of Organics**: Reduces specific gravity
5. **Sample Preparation**: Inadequate drying can affect results

3.3 Particle Size Distribution - Introduction

Particle size distribution (PSD) is the determination of the range of particle sizes present in a soil and their relative proportions. It is fundamental for soil classification and influences many engineering properties.

Significance in Geotechnical Engineering:

1. **Soil Classification**: Forms the primary basis for classifying soils
2. **Drainage Characteristics**: Relates to permeability and drainage
3. **Frost Susceptibility**: Fine-grained soils are more susceptible to frost action
4. **Compaction Characteristics**: Affects optimum moisture content and maximum dry density
5. **Filter Design**: Critical for designing drainage filters
6. **Erosion Resistance**: Relates to susceptibility to erosion
7. **Liquefaction Potential**: Certain gradations are more susceptible to liquefaction

Soil Particle Size Ranges:

According to Indian Standard (IS: 1498), soil particles are classified as:

Soil Type	Particle Size Range
Boulder	> 300mm

Soil Type	Particle Size Range
Cobble	80-300mm
Coarse Gravel	20-80mm
Fine Gravel	4.75-20mm
Coarse Sand	2.0-4.75mm
Medium Sand	0.425-2.0mm
Fine Sand	0.075-0.425mm
Silt	0.002-0.075mm
Clay	< 0.002mm

Methods of Particle Size Analysis:

The method used depends on the size range of particles:

1. **Sieve Analysis**: For coarse-grained soils (sand and gravel)
    - Dry sieving for particles > 4.75mm
    - Wet sieving for particles between 0.075mm and 4.75mm
2. **Sedimentation Analysis**: For fine-grained soils (silt and clay)
    - Hydrometer method
    - Pipette method
3. **Combined Analysis**: For soils with wide range of particle sizes
    - Sieve analysis for portion retained on 0.075mm sieve
    - Sedimentation analysis for portion passing 0.075mm sieve

Factors Affecting Particle Size Distribution:

1. **Geological Origin**: Residual, alluvial, glacial, etc.
2. **Transport Mechanism**: Water, wind, gravity, ice
3. **Weathering Processes**: Physical and chemical breakdown
4. **Human Activities**: Excavation, crushing, screening

Uniformity Coefficient and Coefficient of Curvature:

Two important parameters derived from the particle size distribution curve:

1. **Uniformity Coefficient (Cu)**: $Cu = D60/D10$

    Where:

    - $D60$ = particle diameter at 60% passing
    - $D10$ = particle diameter at 10% passing (effective size)

    Interpretation:

    - $Cu < 2$: Very uniform soil

- Cu = 2-5: Medium uniform soil
- Cu > 5: Well-graded soil

2. **Coefficient of Curvature (Cc)**: Cc = $(D30)^2/(D10 \times D60)$

   Where:

   - D30 = particle diameter at 30% passing

   Interpretation:

   - Cc between 1 and 3 indicates well-graded soil
   - Values outside this range indicate gap-graded or poorly graded soil

3.4 Sieve Analysis - Theory and Procedure

Sieve analysis is a method used to determine the grain size distribution of coarse-grained soils (sand and gravel).

Theory:

The method is based on passing the soil through a series of sieves with progressively smaller openings. The weight of soil retained on each sieve is measured and converted to a percentage of the total sample weight.

Equipment Required:

1. Set of standard IS sieves (typically 100mm, 80mm, 40mm, 20mm, 10mm, 4.75mm, 2.36mm, 1.18mm, 600µm, 425µm, 300µm, 150µm, and 75µm)
2. Sieve shaker (mechanical or electrical)
3. Balance sensitive to 0.1g
4. Oven
5. Brushes for cleaning sieves
6. Mortar and rubber-tipped pestle (for breaking up aggregations)
7. Sample splitter or quartering equipment

Procedure for Dry Sieve Analysis (IS: 2720 Part IV):

1. **Sample Preparation**:
   - Oven dry the soil sample at 105-110°C
   - Carefully break up any aggregations (not individual particles)
   - For coarse-grained soils, take approximately 5-6kg
   - For fine-grained soils, take approximately 500g
2. **Sieving Operation**:
   - Arrange sieves in descending order of opening size (largest at top)
   - Place the prepared sample on the top sieve
   - Cover with a lid and place on the sieve shaker

- Shake for about 10-15 minutes
    - Alternatively, hand shaking can be done with circular and tapping motions
3. **Weighing**:
    - Carefully transfer the soil retained on each sieve to the balance
    - Weigh and record the mass retained on each sieve
    - Check that the sum of weights approximately equals the initial sample weight (allowing for a small loss)
4. **Calculations**:
    - Calculate the percentage retained on each sieve: % Retained = (Weight retained on sieve / Total weight) × 100%
    - Calculate the cumulative percentage retained: Cumulative % Retained = Sum of % retained on all sieves with larger openings + % retained on the current sieve
    - Calculate the percentage passing (or finer): % Passing = 100% - Cumulative % retained

Procedure for Wet Sieve Analysis:

This method is used when the soil contains significant amounts of fine particles (silt and clay) that tend to adhere to larger particles.

1. **Sample Preparation**:
    - Weigh the oven-dried sample
    - Soak the sample in water (with or without a dispersing agent) for several hours
2. **Washing Operation**:
    - Pour the soaked sample onto the 75μm sieve placed over a pan
    - Wash the sample thoroughly with water until the water passing through becomes clear
    - Transfer the retained material to a container
    - Oven dry at 105-110°C
3. **Sieving Operation**:
    - Perform dry sieving on the oven-dried retained material as described above
4. **Calculations**:
    - Calculate the percentage passing the 75μm sieve: % Passing 75μm = [(Original dry weight - Dry weight after washing) / Original dry weight] × 100%
    - Calculate other percentages as in dry sieving

Presentation of Results:

Results are typically presented in two forms:

1. **Tabular Form**:

Sieve Size	Weight Retained (g)	% Retained	Cumulative % Retained	% Passing
4.75mm	25	5.0	5.0	95.0
2.36mm	75	15.0	20.0	80.0
etc.	...	...	...	...

2. **Graphical Form**:
    - Plot the percentage passing (y-axis) against the logarithm of particle size (x-axis)
    - This creates the particle size distribution curve

Limitations of Sieve Analysis:

1. Not suitable for particles smaller than 75µm (requires sedimentation methods)
2. Particle shape affects passage through sieves (elongated particles may pass or be retained based on orientation)
3. Sieving action may break fragile particles
4. Agglomeration of fine particles can lead to inaccurate results

3.6 Particle Size Distribution Curve and Its Uses

The particle size distribution (PSD) curve is a graphical representation of the particle sizes present in a soil and their relative proportions. It is plotted on a semi-logarithmic graph with particle size on the logarithmic x-axis and percentage passing (or finer) on the linear y-axis.

Construction of PSD Curve:

1. Plot the percentage passing (y-axis) against the corresponding particle size (x-axis) for each sieve
2. Connect the plotted points with a smooth curve
3. For a complete analysis, combine the results from sieve analysis and sedimentation analysis

Types of Gradation Curves:

1. **Well-Graded Soil**:
    - Smooth, continuous curve
    - Represents a wide range of particle sizes
    - No excess or deficiency of any particular size
    - Characterized by high Cu (>6 for gravels, >4 for sands) and Cc between 1-3
2. **Poorly-Graded Soil**:
    - Predominantly one particle size (uniform soil)
    - Low Cu values (<4)
    - Characterized by a steep curve
3. **Gap-Graded Soil**:
    - Certain intermediate sizes missing
    - Characterized by a flat or horizontal segment in the curve
    - Cc values outside the range of 1-3
4. **Uniformly-Graded Soil**:
    - Narrow range of particle sizes
    - Nearly vertical curve
    - Cu values close to 1

Important Parameters Derived from PSD Curve:

1. **Effective Size (D10)**:
   - Particle size corresponding to 10% passing
   - Relates to drainage characteristics and permeability
   - Significant in filter design
2. **Uniformity Coefficient (Cu)**:
   - $Cu = D60/D10$
   - Measure of the range of particle sizes
   - Higher values indicate well-graded soils
3. **Coefficient of Curvature (Cc)**:
   - $Cc = (D30)^2/(D10 \times D60)$
   - Indicates the shape of the curve
   - Values between 1 and 3 indicate well-graded soils
4. **D60, D30**:
   - Particle sizes corresponding to 60% and 30% passing
   - Used in calculating Cu and Cc
5. **Fineness Modulus**:
   - Sum of cumulative percentages retained on the standard sieves divided by 100
   - Used primarily for concrete aggregate grading

Engineering Applications of PSD Curve:

1. **Soil Classification**:
   - Primary basis for classifying coarse-grained soils
   - Determines percentages of gravel, sand, silt, and clay
2. **Permeability Estimation**:
   - Empirical correlations exist between D10 and permeability
   - Hazen's formula: $k = C(D10)^2$ (where k = coefficient of permeability, C = constant, D10 in cm)
3. **Filter Design**:
   - Designing granular filters for dams, retaining walls, and drainage systems
   - Filter criteria based on particle size ratios
   - Terzaghi's criteria: $D15(filter)/D85(base) < 4\text{-}5$ and $D15(filter)/D15(base) > 4\text{-}5$
4. **Frost Susceptibility**:
   - Soils with more than 10% finer than 0.02mm are potentially frost susceptible
   - Can identify frost-susceptible soils
5. **Liquefaction Potential**:
   - Uniformly graded fine sands ($D50 \approx 0.2$mm) are most susceptible to liquefaction
   - PSD helps identify such soils
6. **Compaction Characteristics**:
   - Well-graded soils typically achieve higher densities
   - PSD helps predict compaction behavior
7. **Estimating Soil Properties**:

   - Correlations exist between gradation and various properties like CBR, angle of friction, etc.
8. **Evaluating Drainage Characteristics**:
   - Percentage of fine particles affects drainage
   - Soils with high percentage passing 75μm have poor drainage
9. **Assessing Suitability for Various Uses**:
   - Base and sub-base materials for roads
   - Backfill for retaining walls
   - Aggregates for concrete
   - Embankment materials

3.7 Consistency of Soils - Introduction

Soil consistency refers to the relative ease with which soil can be deformed and to the strength with which soil particles are held together. It is a critical property of fine-grained soils (silts and clays) and varies with water content.

Significance of Soil Consistency:

1. **Workability**: Affects the ease of handling, mixing, and compacting soil during construction
2. **Strength**: Relates to bearing capacity and stability
3. **Compressibility**: Influences settlement characteristics
4. **Soil Classification**: Used in classifying fine-grained soils
5. **Construction Planning**: Helps determine suitable construction methods and equipment

States of Consistency:

As water content increases, a fine-grained soil passes through four distinct states:

1. **Solid State**:
   - Soil behaves as a solid
   - Brittle fracture occurs when stressed
   - Volumetric changes due to moisture changes are minimal
2. **Semi-Solid State**:
   - Soil has some plasticity but retains its shape
   - Crumbles when rolled into thin threads
   - Begins to exhibit shrinkage with drying
3. **Plastic State**:
   - Soil can be molded into various shapes without cracking
   - Retains its shape after the molding force is removed
   - Most appropriate state for compaction
4. **Liquid State**:
   - Soil flows like a thick liquid
   - Cannot retain its shape
   - Behaves according to the laws of fluid mechanics

Atterberg Limits:

The water content boundaries between these states are known as Atterberg limits, named after Albert Atterberg who developed them in 1911:

1. **Shrinkage Limit (SL)**:
   - Boundary between solid and semi-solid states
   - Water content at which further reduction in moisture does not cause volume reduction
2. **Plastic Limit (PL)**:
   - Boundary between semi-solid and plastic states
   - Minimum water content at which soil can be rolled into 3mm threads without crumbling
3. **Liquid Limit (LL)**:
   - Boundary between plastic and liquid states
   - Water content at which soil begins to flow like a liquid

Derived Consistency Parameters:

From the Atterberg limits, several important consistency parameters are derived:

1. **Plasticity Index (PI)**:
   - PI = LL - PL
   - Represents the range of water content over which the soil exhibits plastic behavior
   - Indicator of clay content and type
2. **Liquidity Index (LI)**:
   - LI = (w - PL) / (LL - PL)
   - Indicates the soil's natural water content relative to its plastic and liquid limits
   - LI < 0: Soil behaves as semi-solid or solid
   - 0 < LI < 1: Soil behaves as plastic
   - LI > 1: Soil behaves as liquid
3. **Consistency Index (CI)**:
   - CI = (LL - w) / (LL - PL) = 1 - LI
   - Alternative measure of relative consistency
   - Higher values indicate stiffer consistency
4. **Activity (A)**:
   - A = PI / % clay fraction (< 2μm)
   - Indicates the clay mineral type and its influence on soil behavior

Factors Affecting Consistency:

1. **Clay Mineral Type**:
   - Montmorillonite: High PI, very sensitive to water
   - Kaolinite: Low PI, less sensitive to water
2. **Clay Content**:
   - Higher clay content generally means higher plasticity
3. **Organic Content**:

- Increases liquid limit but not plastic limit significantly

4. **Pore Water Chemistry**:
    - Salt concentration affects consistency, particularly for montmorillonite clays
5. **Testing Methods**:
    - Variations in testing procedure can affect results
    - Drying history can affect results for certain soils

3.8 Atterberg's Limits - Liquid and Plastic Limit

Atterberg's limits are a basic measure of the critical water contents of fine-grained soils. They define the boundaries between different states of soil consistency.

Soil Consistency States:

Fine-grained soils can exist in four states, depending on water content:

1. **Solid state**: Soil behaves as a solid, breaks when bent
2. **Semi-solid state**: Soil can be crumbled and deformed
3. **Plastic state**: Soil can be molded into different shapes without cracking
4. **Liquid state**: Soil behaves like a thick liquid

The water contents at the boundaries between these states are known as Atterberg's limits:

- **Shrinkage Limit (SL)**: Boundary between solid and semi-solid states
- **Plastic Limit (PL)**: Boundary between semi-solid and plastic states
- **Liquid Limit (LL)**: Boundary between plastic and liquid states

Liquid Limit (LL)

The liquid limit is defined as the water content at which soil passes from the plastic state to the liquid state, or the minimum water content at which the soil flows under a specified small disturbance.

Casagrande Method (IS: 2720, Part V)

Equipment:

- Casagrande liquid limit device
- Grooving tool
- Balance accurate to 0.01 g
- Oven
- Spatula, porcelain dish, wash bottle

Procedure:

1. Take about 120 g of soil passing through 425 μm sieve
2. Mix with distilled water to form a uniform paste

3. Place a portion of the paste in the cup of the liquid limit device
4. Level the surface and draw a groove using the standard grooving tool
5. Turn the crank at 2 revolutions per second
6. Count the number of blows required to close the groove for a distance of 12 mm
7. Take a sample from the closed portion for water content determination
8. Repeat with different water contents to obtain at least 4 points
9. Plot water content vs. log(number of blows)
10. The water content corresponding to 25 blows is the liquid limit

Cone Penetrometer Method

Equipment:

- Cone penetrometer with a cone of 30° apex angle and 80 g weight
- Sample container
- Balance, oven, and other accessories

Procedure:

1. Prepare soil as in the Casagrande method
2. Place in the container and level the surface
3. Position the cone just touching the soil surface
4. Release the cone for 5 seconds and measure the penetration depth
5. Take a sample for water content determination
6. Repeat with different water contents
7. Plot water content vs. penetration depth
8. The water content corresponding to 20 mm penetration is the liquid limit

Plastic Limit (PL)

The plastic limit is defined as the water content at which soil rolls into threads of 3 mm diameter without breaking.

Equipment:

- Glass plate or unglazed paper
- Balance accurate to 0.01 g
- Oven
- Spatula, porcelain dish

Procedure:

1. Take about 20 g of soil passing through 425 µm sieve
2. Mix with distilled water until plastic
3. Roll a small portion between the palm and the glass plate
4. If the thread cracks when it reaches 3 mm diameter, the plastic limit is reached
5. Collect the crumbled threads for water content determination

6. Repeat at least 3 times and take the average water content

Significance of Atterberg's Limits:

1. **Classification**: Used in various soil classification systems
2. **Foundation Design**: Indicator of potential problems with expansive soils
3. **Compaction**: Influence on optimal compaction conditions
4. **Strength**: Correlation with undrained shear strength
5. **Workability**: Indicator of how easily soil can be worked with during construction

3.9 Plasticity Index and Consistency Index

Plasticity Index (PI)

The plasticity index is the range of water content over which a soil behaves plastically. It is calculated as:

PI = LL - PL

Where:

- PI = Plasticity Index (%)
- LL = Liquid Limit (%)
- PL = Plastic Limit (%)

Interpretation of Plasticity Index:

PI Value	Description	Characteristics
0	Non-plastic	Typically sands, cannot be rolled into 3mm threads
1-5	Slightly plastic	Little cohesion, difficult to roll into threads
5-10	Low plasticity	Can be rolled into threads with some difficulty
10-20	Medium plasticity	Can be rolled into threads easily, moderate cohesion
20-40	High plasticity	Strong cohesion, sticky when wet
>40	Very high plasticity	Extremely cohesive, very sticky when wet

Engineering Significance of PI:

1. **Expansive Potential**:
   - PI < 15: Low expansion potential
   - PI = 15-35: Medium expansion potential
   - PI > 35: High expansion potential
2. **Compressibility**: Higher PI generally indicates higher compressibility
3. **Shear Strength**: Generally, as PI increases, undrained shear strength decreases
4. **Frost Susceptibility**: Soils with low PI are often more frost-susceptible
5. **Permeability**: Higher PI typically indicates lower permeability

Consistency Index (CI)

The consistency index describes the relative consistency (firmness) of a cohesive soil. It is calculated as:

CI = (LL - w)/PI

Where:

- CI = Consistency Index
- LL = Liquid Limit (%)
- w = Natural water content (%)
- PI = Plasticity Index (%)

Interpretation of Consistency Index:

CI Value	Consistency	Description
< 0	Liquid	Behaves like a viscous liquid
0-0.5	Very soft to soft	Easily molded by fingers
0.5-0.75	Medium stiff	Can be molded by strong finger pressure
0.75-1.0	Stiff	Cannot be molded by fingers, can be indented by thumb
> 1.0	Hard	Difficult to indent by thumbnail

Engineering Significance of CI:

1. **Workability**: Lower CI means more difficult to work with in construction
2. **Bearing Capacity**: Higher CI generally indicates higher bearing capacity
3. **Stability**: Higher CI typically means greater stability in excavations and slopes
4. **Settlement**: Lower CI often correlates with higher potential settlement

Combined Use of PI and CI:

Together, the plasticity index and consistency index provide valuable information about:

1. **Soil Type**: For identification and classification
2. **Engineering Behavior**: Strength, compressibility, and stability
3. **Construction Considerations**: Excavation difficulty, need for dewatering, etc.
4. **Design Parameters**: Correlations with other engineering properties

3.10 Liquidity Index - Determination and Significance

Liquidity Index (LI)

The liquidity index indicates how close a soil's natural water content is to its liquid limit. It is calculated as:

LI = (w - PL)/PI

Where:

- LI = Liquidity Index
- w = Natural water content (%)
- PL = Plastic Limit (%)
- PI = Plasticity Index (%)

Determination:

1. Determine the natural water content (w) of the undisturbed soil sample
2. Determine the plastic limit (PL) and liquid limit (LL) of the soil
3. Calculate the plasticity index: PI = LL - PL
4. Calculate the liquidity index using the formula above

Interpretation of Liquidity Index:

LI Value	Description	State
< 0	Semi-solid to solid	Water content below plastic limit
0	At plastic limit	Beginning of plastic behavior
0-1	Plastic	Increasing softness as LI approaches 1
1	At liquid limit	Beginning of liquid behavior
> 1	Liquid	Behaves as a viscous liquid

Engineering Significance:

1. **Sensitivity**:
   - High LI (>1) often indicates sensitive clays that lose strength when disturbed
   - Sensitive clays typically have LI values between 1 and 1.5
2. **Undisturbed Strength**:
   - As LI increases, undisturbed shear strength generally decreases
   - Empirical relationship: cu (kPa) ≈ 170 - 160 × LI (for LI < 1.5)
3. **Remolded Strength**:
   - Higher LI correlates with lower remolded strength
   - Critical for assessing stability after disturbance
4. **Compressibility**:
   - Higher LI indicates higher compressibility
   - Important for settlement predictions
5. **Construction Considerations**:
   - LI > 0.5: May require special handling during excavation
   - LI > 1.0: Likely to require stabilization measures
6. **Consolidation History**:
   - Normally consolidated clays typically have LI ≈ 0.5
   - Overconsolidated clays typically have LI < 0.5
   - Underconsolidated clays typically have LI > 0.5

Comparison with Consistency Index:

The liquidity index (LI) and consistency index (CI) are inversely related:

CI = 1 - LI

Both indices provide the same information but in different ways:

- LI measures how close the soil is to the liquid limit (increasing from 0 at PL to 1 at LL)
- CI measures how far the soil is from the liquid limit (decreasing from 1 at PL to 0 at LL)

The choice between using LI or CI often depends on regional preferences and specific applications.

CHAPTER 4: SOIL CLASSIFICATION SYSTEMS

4.1 Classification of Soil - General Principles

Soil classification systems are frameworks for organizing soils into groups based on their physical properties and engineering behavior. A good classification system should:

1. Be based on simple, inexpensive tests
2. Group soils with similar engineering properties
3. Provide a common language for engineers
4. Be adaptable to a wide range of soils

Purpose of Soil Classification:

1. **Communication**: Providing a standard way to describe soils
2. **Prediction**: Estimating probable soil behavior
3. **Organization**: Systematically categorizing soil data
4. **Preliminary Design**: Making initial design decisions before detailed testing
5. **Construction Planning**: Anticipating potential issues during construction

Classification Criteria:

Various soil properties can be used for classification, including:

1. **Particle Size Distribution**:
   - Percentages of gravel, sand, silt, and clay
   - Gradation characteristics (well-graded, poorly-graded)
2. **Plasticity Characteristics**:
   - Liquid limit (LL)
   - Plastic limit (PL)
   - Plasticity index (PI)
3. **Organic Content**:
   - Presence and amount of organic matter
   - Distinctive odor, color, and texture
4. **Geological Origin**:
   - Residual, alluvial, glacial, etc.
   - Weathering processes and history
5. **Structure**:
   - Undisturbed state characteristics
   - Particle arrangement and bonding

Major Classification Systems:

1. **Indian Standard Classification System (IS: 1498)**:
   - Based on particle size and plasticity
   - Specifically developed for Indian conditions
2. **Unified Soil Classification System (USCS)**:
   - Based on particle size and plasticity
   - Widely used internationally, especially in geotechnical engineering
3. **AASHTO Classification System**:
   - American Association of State Highway and Transportation Officials
   - Focuses on highway subgrade materials
   - Uses group index to evaluate subgrade quality
4. **Textural Classification**:
   - Based solely on particle size proportions
   - Often used in agricultural applications
   - Represented by the USDA textural triangle
5. **Pedological Classification**:
   - Based on soil formation processes
   - Used primarily in agriculture and environmental sciences

General Classification Process:

1. Conduct basic laboratory tests:
   - Grain size analysis (sieve and hydrometer)
   - Atterberg limits (liquid and plastic limits)
   - Organic content determination (if needed)
2. Determine whether the soil is coarse-grained or fine-grained:
   - Coarse-grained: >50% retained on 0.075 mm sieve
   - Fine-grained: >50% passing 0.075 mm sieve
3. For coarse-grained soils, evaluate:
   - Gravel vs. sand proportions
   - Gradation characteristics
   - Fine content and plasticity
4. For fine-grained soils, evaluate:
   - Plasticity characteristics
   - Organic content
   - Compressibility indications
5. Assign classification symbols and descriptive terms
6. Include additional descriptive information as needed

4.2 I.S. Classification System

The Indian Standard Soil Classification System (IS: 1498) is a classification system specifically developed for Indian soils. It is similar to the Unified Soil Classification System but has some modifications to suit Indian conditions.

Major Groups in IS Classification:

The IS system divides soils into three major groups:

1. **Coarse-Grained Soils**: More than 50% retained on 75 μm (0.075 mm) IS sieve
   - **Gravels (G)**: More than 50% of coarse fraction retained on 4.75 mm IS sieve
   - **Sands (S)**: More than 50% of coarse fraction passing 4.75 mm IS sieve
2. **Fine-Grained Soils**: More than 50% passing 75 μm (0.075 mm) IS sieve
   - **Silts (M)**
   - **Clays (C)**
   - **Organic Soils (O)**
3. **Highly Organic Soils and Peat (Pt)**: Primarily organic matter, dark in color, and organic odor

Subdivision of Coarse-Grained Soils:

Coarse-grained soils are further subdivided based on:

1. **Gradation**:
   - **Well-graded (W)**: Wide range of particle sizes with no intermediate sizes missing
   - **Poorly-graded (P)**: Uniform particle size or missing some intermediate sizes
2. **Fine Content**:
   - **Clean**: Less than 5% fines
   - **With fines**: More than 12% fines
   - **Borderline**: 5-12% fines

The complete symbols for coarse-grained soils are:

- **GW**: Well-graded gravel
- **GP**: Poorly-graded gravel
- **GM**: Silty gravel (fines are non-plastic or slightly plastic)
- **GC**: Clayey gravel (fines are plastic)
- **SW**: Well-graded sand
- **SP**: Poorly-graded sand
- **SM**: Silty sand (fines are non-plastic or slightly plastic)
- **SC**: Clayey sand (fines are plastic)

Subdivision of Fine-Grained Soils:

Fine-grained soils are subdivided based on plasticity characteristics:

1. **Liquid Limit**:
   - **Low Plasticity (L)**: LL < 35%
   - **Intermediate Plasticity (I)**: LL = 35-50%
   - **High Plasticity (H)**: LL > 50%
2. **Organic Content**:
   - Organic soils have significantly lower liquid limit after oven drying

The complete symbols for fine-grained soils are:

- **ML**: Silt of low plasticity
- **MI**: Silt of intermediate plasticity
- **MH**: Silt of high plasticity
- **CL**: Clay of low plasticity
- **CI**: Clay of intermediate plasticity
- **CH**: Clay of high plasticity
- **OL**: Organic soil of low plasticity
- **OI**: Organic soil of intermediate plasticity
- **OH**: Organic soil of high plasticity

Classification Procedure:

1. **Determine Coarse-Grained vs. Fine-Grained**:
   - If >50% retained on 75 µm sieve: Coarse-grained
   - If >50% passes 75 µm sieve: Fine-grained
2. **For Coarse-Grained Soils**:
   - Determine gravel vs. sand (4.75 mm sieve)
   - Check gradation using coefficients:
     - $Cu = D60/D10$ (Uniformity coefficient)
     - $Cc = (D30)^2/(D10 \times D60)$ (Coefficient of curvature)
   - For gravels:
     - GW: $Cu > 4$ and $1 < Cc < 3$
     - GP: Not meeting GW criteria
   - For sands:
     - SW: $Cu > 6$ and $1 < Cc < 3$
     - SP: Not meeting SW criteria
   - If fines >12%, determine plasticity of fines to classify as M or C
3. **For Fine-Grained Soils**:
   - Determine liquid limit and plastic limit
   - Plot on plasticity chart to distinguish between M and C
   - Classify based on liquid limit range (L, I, H)
   - Check for organic content if suspected

Plasticity Chart for Fine-Grained Soils:

The IS plasticity chart has:

- X-axis: Liquid limit (%)
- Y-axis: Plasticity index (%)
- A-line: $PI = 0.73(LL - 20)$

Soils plotting:

- Above A-line: Classified as clays (C)

- Below A-line: Classified as silts (M)
- Close to A-line: May have dual symbols (e.g., CL-ML)

Boundary Classifications:

For soils falling on boundaries between groups, dual symbols may be used:

- Example: SC-SM for sand with fines at boundary between clayey and silty
- Example: CL-ML for fine-grained soil at boundary between clay and silt

Engineering Significance:

Each soil group tends to have characteristic engineering properties:

1. **GW, SW**: Good bearing strength, good drainage, good compaction characteristics
2. **GP, SP**: Good drainage, moderate compaction, moderate bearing capacity
3. **GM, SM**: Fair to poor drainage, good stability, frost susceptible
4. **GC, SC**: Impervious, high shear strength, low compressibility
5. **ML, MI**: Low stability, high frost heave potential, low permeability
6. **CL, CI**: Medium compressibility, medium plasticity, low permeability
7. **MH, CH**: High compressibility, poor stability, high shrink-swell potential
8. **OL, OH, Pt**: Very high compressibility, very poor stability, unsuitable for construction

4.3 Plasticity Chart and Its Applications

The plasticity chart is a graphical tool used in soil classification systems to categorize fine-grained soils based on their plasticity characteristics. It was originally developed by Arthur Casagrande and is an integral part of the IS Classification System.

Components of the Plasticity Chart:

1. **Coordinate System**:
   - X-axis: Liquid limit (LL)
   - Y-axis: Plasticity index (PI)
2. **A-Line**:
   - Equation: $PI = 0.73(LL - 20)$
   - Empirically separates clays (above) from silts and organic soils (below)
3. **B-Line**:
   - Horizontal line at $PI = 7$
   - Helps differentiate low-plasticity materials
4. **Vertical Divisions**:
   - In IS Classification:
     - Low plasticity: $LL < 35\%$
     - Intermediate plasticity: $LL = 35\text{-}50\%$
     - High plasticity: $LL > 50\%$
   - In Unified Classification:

    - Low plasticity: LL < 50%
    - High plasticity: LL ≥ 50%

Using the Plasticity Chart:

To classify a fine-grained soil:

1. Determine the liquid limit (LL) and plastic limit (PL)
2. Calculate the plasticity index: PI = LL - PL
3. Plot the point (LL, PI) on the plasticity chart
4. Determine the classification based on the region where the point falls

Classification Regions on IS Plasticity Chart:

1. **CL**: Clay of low plasticity (above A-line, LL < 35%)
2. **CI**: Clay of intermediate plasticity (above A-line, LL = 35-50%)
3. **CH**: Clay of high plasticity (above A-line, LL > 50%)
4. **ML**: Silt of low plasticity (below A-line, LL < 35%)
5. **MI**: Silt of intermediate plasticity (below A-line, LL = 35-50%)
6. **MH**: Silt of high plasticity (below A-line, LL > 50%)
7. **CL-ML**: Silty clay of low plasticity (on/near A-line, LL < 35%)

Organic soils (OL, OI, OH) plot in the same regions as ML, MI, and MH but are identified by other criteria (color, odor, significant LL reduction after oven drying).

Applications of the Plasticity Chart:

1. **Soil Classification**:
    - Primary tool for classifying fine-grained soils
    - Essential component of engineering soil classification systems
2. **Engineering Behavior Prediction**:
    - Indicator of potential swelling and shrinkage
    - Estimation of compressibility and strength characteristics
    - Assessment of workability and trafficability
3. **Correlation with Other Properties**:
    - Activity (A = PI/% clay fraction)
    - Compressibility index ($C_c \approx 0.009(LL - 10)$)
    - Shrinkage potential and swell index
4. **Foundation Design**:
    - CH, MH soils may require special foundation considerations
    - CL, ML soils generally have moderate engineering properties
5. **Road Construction**:
    - Subgrade evaluation
    - Selection of stabilization methods based on plasticity characteristics
6. **Embankment Design**:
    - Selection of appropriate fill materials

   - Estimation of compaction characteristics
7. **Problem Soil Identification**:
   - Expansive soils: High LL and PI, plotting well above A-line
   - Liquefiable soils: Low plasticity silts (ML)
   - Collapsible soils: Low plasticity, low density

Limitations of the Plasticity Chart:

1. Only applicable to fine-grained soils or the fine fraction of coarse-grained soils
2. Does not account for geological origin or mineralogical composition
3. Requires laboratory testing (not a field classification method)
4. Does not directly measure strength or compressibility
5. May not capture behavior of unusual soils (e.g., volcanic ash, lateritic soils)

Expansions and Modifications:

1. **Activity Chart**:
   - Plots PI vs. clay fraction percentage
   - Helps identify mineralogical influence
2. **Plasticity Number (LI × PI)**:
   - Combined indicator considering both plasticity and natural state
3. **Comparative Charting**:
   - Comparing results before and after treatments
   - Evaluating effects of additives on plasticity characteristics

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CHAPTER 5: PERMEABILITY AND SEEPAGE

5.1 Concept of Permeability and Darcy's Law

Permeability is one of the most important properties of soil that describes the ease with which water can flow through soil pores. In geotechnical engineering, understanding soil permeability is crucial for:

- Foundation design
- Seepage analysis in dams and embankments
- Dewatering systems for excavations
- Slope stability analysis

Darcy's Law: In 1856, Henri Darcy established the fundamental law governing the flow of water through soils. Darcy's Law states that the velocity of flow through a porous medium is directly proportional to the hydraulic gradient.

Mathematically, it is expressed as:
$v = k \times i$

Where:

- v = discharge velocity or superficial velocity (m/s)
- k = coefficient of permeability or hydraulic conductivity (m/s)
- i = hydraulic gradient (dimensionless)

The discharge or flow rate (q) through a soil sample of cross-sectional area A is given by:
$q = k \times i \times A$

Darcy's law is valid for laminar flow, which is typically the case in most soils. The law assumes:

1. The soil is fully saturated
2. Flow is laminar (not turbulent)
3. The soil is homogeneous
4. There is no volume change in the soil during flow

5.2 Coefficient of Permeability

The coefficient of permeability (k) is a measure of the ease with which water flows through soil. It has units of velocity (m/s or cm/s).

Typical values for different soil types:

- Gravels: 10^-2 to 10^0 m/s
- Sands: 10^-5 to 10^-2 m/s
- Silts: 10^-9 to 10^-5 m/s
- Clays: 10^-11 to 10^-9 m/s

From these values, we can observe that:

- Coarse-grained soils (sands and gravels) have high permeability
- Fine-grained soils (silts and clays) have low permeability

For layered soils, we consider:

1. **Horizontal flow through layered soil**:
   - Equivalent k (horizontal) = $(k_1h_1 + k_2h_2 + ... + k_nh_n) / (h_1 + h_2 + ... + h_n)$
   - This is the weighted average based on layer thickness
2. **Vertical flow through layered soil**:
   - Equivalent k (vertical) = $(h_1 + h_2 + ... + h_n) / (h_1/k_1 + h_2/k_2 + ... + h_n/k_n)$
   - This is the harmonic mean

5.3 Factors Affecting Permeability

The permeability of soil is influenced by several factors:

1. **Particle Size**: As particle size increases, permeability increases. Coarse-grained soils (gravels and sands) have higher permeability than fine-grained soils (silts and clays).
2. **Void Ratio**: Higher void ratio leads to higher permeability. According to Kozeny-Carman equation, for granular soils:
3. $k \propto e^3/(1+e)$

   where e is the void ratio.

4. **Degree of Saturation**: Permeability is maximum when the soil is fully saturated. Partially saturated soils have lower permeability due to air bubbles blocking the flow paths.
5. **Soil Structure**: The arrangement of soil particles affects permeability:
   - Flocculated clay structures (random orientation) have higher permeability
   - Dispersed clay structures (parallel orientation) have lower permeability
6. **Temperature**: As water temperature increases, its viscosity decreases, resulting in higher permeability:
7. $k_T = k_{20} \times (\eta_{20}/\eta_T)$

   where η is the viscosity of water and T is the temperature in °C.

8. **Soil Composition**: The presence of clay minerals significantly reduces permeability due to their electrical properties and ability to adsorb water.
9. **Entrapped Air or Gas**: Air bubbles in soil pores reduce the effective flow area, decreasing permeability.

5.4 Constant Head Permeability Test

The constant head permeability test is used to determine the coefficient of permeability of coarse-grained soils (sands and gravels).

Apparatus:

- Constant head permeameter
- Soil sample container
- Manometers
- Measuring cylinder and stopwatch
- Filter materials (gravel and screens)

Procedure:

1. The soil sample is placed in a cylindrical container with filter materials at both ends
2. Water is allowed to flow through the sample under a constant head difference
3. The quantity of water flowing through the sample is collected and measured over a known time period
4. The coefficient of permeability is calculated using Darcy's law

Calculation:
$k = QL/(Ath)$

Where:

- k = coefficient of permeability (cm/s)
- Q = quantity of water collected (cm^3)
- L = length of soil sample (cm)
- A = cross-sectional area of sample (cm^2)
- t = time of collection (seconds)
- h = constant head difference (cm)

Advantages:

- Simple and reliable for coarse-grained soils
- Allows for steady-state flow conditions
- Can be performed with relatively simple equipment

Limitations:

- Not suitable for fine-grained soils (silts and clays)
- Requires careful preparation to avoid sample disturbance
- May underestimate field permeability due to boundary effects

5.5 Falling Head Permeability Test

The falling head permeability test is used to determine the coefficient of permeability of fine-grained soils (silts and clays) with low permeability.

Apparatus:

- Falling head permeameter
- Soil sample container
- Graduated standpipe
- Timer
- Filter materials

Procedure:

1. The soil sample is placed in a cylindrical container with filter materials at both ends
2. A graduated standpipe is attached to the top of the sample
3. Water is filled in the standpipe to an initial height
4. Water flows through the sample, causing the water level in the standpipe to fall
5. The time taken for the water level to fall from an initial height (h_1) to a final height (h_2) is recorded

Calculation:

$k = (aL/At) \times \ln(h_1/h_2)$

Where:

- k = coefficient of permeability (cm/s)
- a = cross-sectional area of standpipe (cm^2)
- L = length of soil sample (cm)
- A = cross-sectional area of sample (cm^2)
- t = time for water to fall from h_1 to h_2 (seconds)
- h_1 = initial head (cm)
- h_2 = final head (cm)

Advantages:

- Suitable for fine-grained soils with low permeability
- Requires less water than constant head test
- Can measure very low permeability values

Limitations:

- More complex calculation
- Non-steady state flow conditions
- Greater potential for errors in measuring time and head differences

CHAPTER 6: COMPACTION AND CONSOLIDATION

6.1 Compaction - Principles and Theory

Compaction is the process of increasing soil density by applying mechanical energy to reduce air voids in the soil. This is different from consolidation, which involves the expulsion of water from soil pores over time.

Principles of Compaction:

1. Compaction increases soil density by expelling air from the soil voids
2. Water acts as a lubricant, helping particles slide past each other during compaction
3. Beyond optimum moisture content, water starts filling voids that could be occupied by soil particles
4. Compaction improves soil properties like strength, stiffness, and permeability

Theory of Compaction: The degree of compaction depends on:

1. Moisture content of the soil
2. Type and amount of compaction energy applied
3. Soil type and gradation
4. Method of compaction

For a given compaction effort, there exists an optimum moisture content (OMC) at which maximum dry density is achieved. This relationship is represented by the compaction curve.

Benefits of Compaction:

1. Increased shear strength
2. Reduced compressibility
3. Decreased permeability
4. Reduced frost susceptibility
5. Prevention of settlement
6. Increased soil bearing capacity

6.2 Light and Heavy Compaction Test

Standard Proctor Test (Light Compaction): The Standard Proctor Test was developed by R.R. Proctor in 1933 to determine the relationship between moisture content and dry density of soils.

Apparatus:

- Cylindrical mold (volume = 944 cm^3, diameter = 10.2 cm)

- Detachable base plate and collar
- Compaction rammer (weight = 2.5 kg, drop height = 30.5 cm)
- Balance, oven, mixing tools

Procedure:

1. Soil is mixed with varying amounts of water
2. The moist soil is compacted in the mold in three equal layers
3. Each layer receives 25 blows from the standard rammer
4. The compaction energy is approximately 600 kJ/m³
5. The compacted soil weight and moisture content are determined
6. The test is repeated for different moisture contents

Modified Proctor Test (Heavy Compaction): The Modified Proctor Test was developed to represent heavier field compaction equipment.

Differences from Standard Proctor:

- Heavier rammer (4.5 kg instead of 2.5 kg)
- Greater drop height (45.7 cm instead of 30.5 cm)
- Five layers instead of three
- 25 blows per layer (same as Standard Proctor)
- Compaction energy is approximately 2700 kJ/m³ (4.5 times that of Standard Proctor)

Comparison:

Parameter	Standard Proctor	Modified Proctor
Rammer weight	2.5 kg	4.5 kg
Drop height	30.5 cm	45.7 cm
Number of layers	3	5
Blows per layer	25	25
Compaction energy	600 kJ/m³	2700 kJ/m³
Typical max. dry density	Lower	Higher
Typical OMC	Higher	Lower

6.3 Optimum Moisture Content and Maximum Dry Density

Optimum Moisture Content (OMC) is the moisture content at which maximum dry density is achieved for a given compaction effort.

Maximum Dry Density (MDD) is the highest dry density that can be achieved for a given soil using a specific compaction effort.

Compaction Curve: When dry density is plotted against moisture content, a bell-shaped curve is obtained:

- At low moisture contents, soil is stiff and resists compaction
- As moisture content increases, water lubricates the particles, allowing better compaction
- At OMC, maximum dry density is achieved
- Beyond OMC, water starts occupying space that could be taken by soil particles, reducing dry density

Mathematical Relationships: Dry density (γd) is related to bulk density (γ) and moisture content (w) by:
$\gamma d = \gamma/(1+w)$

Where:

- γd = dry density
- γ = bulk density
- w = moisture content (as a decimal)

Factors Affecting OMC and MDD:

1. **Soil Type**:
   - Coarse-grained soils: Lower OMC (8-12%), higher MDD
   - Fine-grained soils: Higher OMC (15-30%), lower MDD
2. **Compaction Energy**:
   - Higher compaction energy → Higher MDD and lower OMC
   - Lower compaction energy → Lower MDD and higher OMC
3. **Grain Size Distribution**:
   - Well-graded soils have higher MDD than poorly graded soils
   - Uniformly graded soils have lower MDD
4. **Soil Mineralogy**:
   - Clay mineralogy affects OMC significantly
   - Montmorillonite clays have higher OMC than kaolinite clays

6.4 Zero Air Void Line and Factors Affecting Compaction

Zero Air Void Line (ZAVL) represents the theoretical maximum dry density that can be achieved at various moisture contents if all air is removed from the soil (100% saturation).

The equation for ZAVL is:
$\gamma d(ZAV) = Gs \times \gamma w/(1 + w \times Gs)$

Where:

- $\gamma d(ZAV)$ = dry density at zero air voids
- Gs = specific gravity of soil solids
- γw = unit weight of water
- w = moisture content (as a decimal)

Properties of ZAVL:

1. It is a hyperbolic curve
2. All compaction curves lie below this line
3. It serves as a check on compaction test results (no experimental point should lie above ZAVL)
4. As moisture content increases, the gap between the compaction curve and ZAVL decreases

Factors Affecting Compaction:

1. **Soil Type**:
   - Coarse-grained soils: Steep compaction curves, lower OMC, higher MDD
   - Fine-grained soils: Flatter compaction curves, higher OMC, lower MDD
   - Plastic soils: Very flat compaction curves, high OMC, low MDD
2. **Compaction Energy**:
   - Higher energy shifts the compaction curve upward and to the left
   - Lower energy shifts the compaction curve downward and to the right
3. **Compaction Method**:
   - Dynamic compaction (impact): Effective for all soil types
   - Static compaction (pressure): Better for cohesive soils
   - Kneading compaction (manipulation): Simulates field roller compaction better
4. **Moisture Content**:
   - Dry of optimum: Soil is stiff and resists compaction
   - At optimum: Maximum efficiency of compaction
   - Wet of optimum: Soil becomes soft and difficult to compact properly
5. **Soil Structure**:
   - Remolded soils compact differently than undisturbed soils
   - Previous compaction history affects subsequent compaction behavior

6.5 Field Compaction Methods and Their Suitability

Various field compaction methods are available, each suitable for specific soil types and project requirements:

1. **Smooth Wheel Rollers (Static)**:
   - Equipment: Steel drum rollers with smooth surfaces
   - Mechanism: Static pressure and manipulation
   - Suitable for: Granular soils, thin lifts of clay
   - Compaction depth: 15-30 cm
   - Advantages: Provide smooth finished surface
   - Limitations: Limited effectiveness in cohesive soils
2. **Pneumatic Tire Rollers**:
   - Equipment: Multiple rubber tires with overlapping paths
   - Mechanism: Kneading action combined with pressure
   - Suitable for: Most soil types, especially silty and clayey soils
   - Compaction depth: 20-40 cm
   - Advantages: Good depth effect, suitable for various soil types

- Limitations: May not provide smooth finished surface

3. **Sheepsfoot Rollers**:
    - Equipment: Steel drums with projecting feet
    - Mechanism: Kneading action at depth
    - Suitable for: Cohesive soils (clays and silty clays)
    - Compaction depth: 15-25 cm
    - Advantages: Effective for clay compaction, breaks down clods
    - Limitations: Poor surface compaction, not suitable for granular soils
4. **Vibratory Rollers**:
    - Equipment: Steel drums with vibrating mechanism
    - Mechanism: Vibration + pressure
    - Suitable for: Granular soils, gravels, sand
    - Compaction depth: 30-100 cm
    - Advantages: High efficiency, greater depth effect
    - Limitations: Less effective for cohesive soils, may damage adjacent structures
5. **Rammers and Plate Compactors**:
    - Equipment: Hand-operated or small mechanical compactors
    - Mechanism: Impact or vibration
    - Suitable for: Confined areas, trench backfill, small areas
    - Compaction depth: 15-30 cm
    - Advantages: Portable, suitable for restricted access areas
    - Limitations: Low productivity, labor intensive
6. **Impact Compactors**:
    - Equipment: Heavy weights dropped from height
    - Mechanism: High-energy impact
    - Suitable for: Deep compaction, collapsible soils
    - Compaction depth: Up to several meters
    - Advantages: Very deep compaction effect
    - Limitations: Specialized equipment, potential damage to adjacent structures

Suitability Based on Soil Type:

Soil Type	Most Suitable Compaction Methods
Gravel	Vibratory rollers, Impact compactors
Sand	Vibratory rollers, Vibrating plates
Silt	Pneumatic tire rollers, Sheepsfoot rollers
Clay	Sheepsfoot rollers, Pneumatic tire rollers
Mixed soils	Pneumatic tire rollers

6.6 Consolidation vs Compaction - Key Differences

Although both consolidation and compaction result in volume reduction and density increase in soils, they are fundamentally different processes:

Parameter	Compaction	Consolidation
Definition	Mechanical process of increasing soil density by expelling air	Time-dependent process of soil volume reduction due to expulsion of water

Mechanism	Mechanical energy application	Application of sustained load
Medium expelled	Air	Water
Time requirement	Immediate	Long-term (days to years)
Saturation state	Partially saturated soils	Fully saturated soils
Process control	Controllable by compaction effort	Depends on soil properties and drainage conditions
Reversibility	Largely irreversible	Partially reversible (elastic component)
Field application	Construction process	Natural process or induced by structure loads
Soil type relevance	All soil types	Primarily cohesive soils (clays and silts)
Effect on structure	Improves soil structure	May disturb soil structure

Key Concepts in Consolidation:

1. Consolidation is the gradual expulsion of water from soil pores under sustained loading
2. It occurs in saturated or nearly saturated fine-grained soils
3. The rate of consolidation depends on soil permeability and drainage conditions
4. Primary consolidation is due to dissipation of excess pore water pressure
5. Secondary consolidation (creep) occurs after primary consolidation due to soil skeleton adjustment

CHAPTER 7: SHEAR STRENGTH OF SOIL

7.1 Concept of Shear Strength

Shear strength is the internal resistance offered by soil to shearing stresses. It is one of the most important engineering properties of soil, as it determines:

- Stability of slopes
- Bearing capacity of foundations
- Earth pressure on retaining structures
- Stability of excavations

Shear Failure: Shear failure occurs when the shear stress applied to a soil mass exceeds its shear strength. This typically occurs along a failure surface or plane.

Components of Shear Strength: The shear strength of soil is derived from two main components:

1. **Frictional Resistance**: Develops due to interlocking of particles and friction between particles in contact
2. **Cohesion**: Develops due to molecular attraction between soil particles (significant in clays)

Factors Affecting Shear Strength:

1. Effective stress
2. Soil type and mineralogy
3. Particle shape and size distribution
4. Density or void ratio
5. Soil structure
6. Stress history
7. Drainage conditions
8. Rate of loading

7.2 Mohr-Coulomb Failure Theory

The Mohr-Coulomb failure theory is the most widely used criterion for representing the shear strength of soils. According to this theory, failure occurs when the shear stress on any plane in a soil mass reaches a value that depends linearly on the normal stress on that plane.

Mathematical Expression:

$\tau f = c + \sigma \tan \varphi$

Where:

- τf = shear strength (shear stress at failure)
- c = cohesion
- σ = normal stress on the failure plane
- φ = angle of internal friction

In terms of effective stress:
$\tau f = c' + \sigma' \tan \varphi'$

Where:

- c' = effective cohesion
- σ' = effective normal stress
- φ' = effective angle of internal friction

Mohr Circle Representation:

- The state of stress at a point can be represented by a Mohr circle
- Failure occurs when the Mohr circle touches the Mohr-Coulomb failure envelope
- The failure envelope is a straight line with equation $\tau = c + \sigma \tan \varphi$

Special Cases:

1. **Cohesionless soils (sands)**:
   - c = 0
   - $\tau f = \sigma \tan \varphi$
2. **Undrained loading of saturated clays**:
   - $\varphi = 0$ (apparent)
   - τf = cu (undrained cohesion

7.3 Cohesion and Angle of Internal Friction

The shear strength parameters, cohesion (c) and angle of internal friction (φ), represent the fundamental characteristics of soil resistance to shearing.

Cohesion (c): Cohesion is the component of shear strength that exists even when the normal stress is zero. It represents the attraction between soil particles.

- **True Cohesion**: Results from interparticle forces (electrostatic and electromagnetic) and cementation
- **Apparent Cohesion**: Temporary cohesion due to capillary stresses in partially saturated soils

Typical values:

- Clean sands: 0 kPa (no cohesion)
- Silty sands: 0-10 kPa
- Silts: 0-20 kPa
- Soft clays: 10-25 kPa
- Medium clays: 25-50 kPa
- Stiff clays: 50-100 kPa
- Very stiff clays: 100-200 kPa

Angle of Internal Friction (φ): The angle of internal friction represents the resistance to sliding between soil particles. It depends on:

- Particle shape (angular particles have higher φ)
- Particle size distribution (well-graded soils have higher φ)
- Surface roughness of particles
- Density or void ratio (denser soils have higher φ)
- Mineralogy (especially for clay soils)

Typical values:

- Loose sand: 28°-30°
- Medium dense sand: 30°-36°
- Dense sand: 36°-41°
- Gravel: 35°-45°
- Silt: 26°-30°
- Soft clay: 5°-10°
- Medium clay: 10°-20°
- Stiff clay: 20°-30°

Relationship with Effective Stress: Both c and φ can be expressed in terms of total stress or effective stress:

- Total stress parameters: c, φ
- Effective stress parameters: c', φ'

For most geotechnical applications, effective stress parameters are more relevant since they control long-term behavior.

7.4 Strength Envelope for Different Types of Soil

The strength envelope is a graphical representation of the Mohr-Coulomb failure criterion in the τ-σ plane. Different soil types have distinctive strength envelopes:

1. Clean Sands and Gravels (Cohesionless Soils):

- Straight line passing through origin (c = 0)
- Equation: $\tau_f = \sigma' \tan \varphi'$

- Envelope is unaffected by drainage conditions
- Strength depends primarily on relative density and particle angularity

2. Normally Consolidated Clays:

- Approximately linear in the normal range of stresses
- Low effective cohesion ($c' \approx 0$)
- Effective friction angle typically 20°-30°
- Under undrained conditions, appears as a horizontal line ($\varphi = 0$) with $\tau_f = c_u$

3. Overconsolidated Clays:

- Curved envelope at low stress levels, becoming linear at higher stresses
- Significant effective cohesion ($c' > 0$)
- Effective friction angle similar to normally consolidated clays
- Undrained strength depends on overconsolidation ratio

4. Silts:

- Intermediate behavior between sands and clays
- Small effective cohesion
- Friction angle typically 26°-30°
- Sensitive to drainage conditions

5. Organic Soils:

- Generally lower strength than inorganic soils
- High compressibility affects strength behavior
- More pronounced secondary compression effects

Curved Strength Envelopes: For many soils, especially at a wide range of stress levels, the strength envelope may not be linear. In such cases, it can be represented by:

- Non-linear equations (e.g., power functions)
- Piecewise linear approximations
- Modified failure criteria (e.g., Hoek-Brown criterion for rock)

7.5 Direct Shear Test and Triaxial Shear Test

Direct Shear Test:

The direct shear test is one of the simplest and oldest methods for determining the shear strength parameters of soils.

Apparatus:

- Shear box (split horizontally)

- Loading frame
- Normal load application system
- Shear force application system
- Displacement measurement devices

Procedure:

1. The soil sample is placed in the shear box
2. A normal load is applied to the top of the sample
3. The top half of the box is moved horizontally relative to the bottom half at a constant rate
4. Shear force and displacement are measured throughout the test
5. The test is repeated with different normal loads

Calculations:

- Shear stress = Shear force / Area of sample
- Normal stress = Normal force / Area of sample
- Plot shear stress vs. shear displacement for each normal stress
- Determine peak and residual shear strength
- Plot peak shear stress vs. normal stress for multiple tests
- Determine c and φ from the best-fit line

Advantages:

- Simple and quick test
- Easily understood concept
- Direct measurement of shear strength along a predetermined plane
- Can test undisturbed, remolded, or compacted samples

Limitations:

- Forced failure plane (may not be the weakest)
- Non-uniform stress distribution
- Limited control of drainage conditions
- Progressive failure along the shear plane
- Cannot measure pore water pressure

Triaxial Shear Test:

The triaxial test is a more sophisticated test that allows control of drainage conditions and measurement of pore water pressure.

Apparatus:

- Triaxial cell with confining pressure system
- Loading frame for axial load application
- Pore pressure measurement system

- Volume change measurement system
- Data acquisition system

Procedure:

1. The cylindrical soil sample is encased in a rubber membrane
2. The sample is placed in the triaxial cell filled with water
3. Confining pressure (σ_3) is applied to the sample
4. Axial stress (σ_1) is increased until failure
5. Deformation and, if required, pore pressure are measured

Types of Triaxial Tests:

1. **Unconsolidated Undrained (UU)**:
   - No consolidation before shearing
   - No drainage during shearing
   - Quick test for total stress analysis
   - Used for short-term stability analysis
2. **Consolidated Undrained (CU)**:
   - Sample consolidated under confining pressure before shearing
   - No drainage during shearing
   - Pore pressure measured during shearing
   - Provides both total and effective stress parameters
3. **Consolidated Drained (CD)**:
   - Sample consolidated under confining pressure before shearing
   - Drainage allowed during shearing (very slow rate)
   - No excess pore pressure develops
   - Provides effective stress parameters

Advantages:

- Complete control of drainage conditions
- Measurement of pore water pressure possible
- Uniform stress conditions until failure
- Failure occurs along natural weakness planes
- More representative of field conditions

Limitations:

- More complex and time-consuming
- Requires more sophisticated equipment
- End effects can influence results
- Membrane correction may be necessary

7.6 Unconfined Compression Test and Vane-Shear Test

Unconfined Compression Test:

The unconfined compression test is a simplified form of the triaxial test for cohesive soils, with no confining pressure ($\sigma_3 = 0$).

Apparatus:

- Loading frame
- Load measurement device
- Deformation measurement device
- Specimen trimming tools

Procedure:

1. A cylindrical soil sample is prepared (height/diameter ratio = 2)
2. The sample is placed in the loading frame without any confining pressure
3. Axial load is applied at a constant rate of strain
4. Load and deformation are measured until failure

Calculations:

- Axial stress = Load / Cross-sectional area (corrected for deformation)
- Axial strain = Deformation / Initial height
- Unconfined compressive strength (qu) = Maximum axial stress
- Undrained shear strength (cu) = qu/2

Interpretation: For saturated clays, the unconfined compression test represents an undrained test with $\varphi = 0$. According to the Mohr-Coulomb criterion:

- Failure envelope is horizontal ($\varphi = 0$)
- cu = qu/2
- Mohr circle at failure touches the failure envelope at its rightmost point

Advantages:

- Simple and quick
- No complicated equipment needed
- Provides direct measure of undrained shear strength
- Suitable for intact cohesive soils

Limitations:

- Only applicable to cohesive soils that can stand unsupported
- Does not provide effective stress parameters
- Sensitive to sample disturbance
- No control of drainage conditions

Vane-Shear Test:

The vane-shear test is used for measuring the undrained shear strength of very soft to medium stiff clays, especially when sample disturbance is a concern.

Apparatus:

- Vane with four blades at right angles
- Torque measurement device
- Vane rotation mechanism
- Guide for vertical insertion

Field Procedure:

1. The vane is pushed into the soil to the desired depth
2. After a waiting period, the vane is rotated at a constant rate (6°/min)
3. Maximum torque is measured
4. The vane is rapidly rotated several times, and the test is repeated to determine remolded strength

Laboratory Procedure: Similar to field procedure but using a smaller vane in soil samples.

Calculations: For a rectangular vane with height H and diameter D:
$cu = T / [\pi \times D^2 \times (H/2 + D/6)]$

Where:

- cu = undrained shear strength
- T = maximum torque

Correction Factors: Vane test results often need correction factors depending on:

- Soil plasticity
- Rate of loading
- Anisotropy of soil strength

The corrected undrained shear strength is:
$cu(corrected) = cu(measured) \times \mu$

Where μ is the correction factor (typically 0.5-0.9 for most clays).

Advantages:

- Can be performed in situ with minimal disturbance
- Quick and simple
- Suitable for very soft soils where sampling is difficult
- Provides both peak and remolded strengths (sensitivity)

Limitations:

- Only applicable to cohesive soils
- Affected by soil anisotropy
- Drainage may occur around the vane blades
- Not suitable for soils with inclusions (gravel, shells)
