



PRACTICAL MANUAL ON SOIL PHYSICS

Measurement and Interpretation of Soil Physical Properties

ICAR-National Institute of Abiotic Stress Management
Baramati, Pune, Maharashtra 413115

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Measurement and Interpretation of Soil Physical Properties

Prepared for

M.Sc. (Ag.) / Ph.D. Programmes

ICAR–ARS, NET and Allied Competitive Examinations

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PREFACE

Soil physics forms the foundation for understanding soil–water–plant relationships and the physical processes governing water movement, aeration, root growth, and soil structural stability. This practical manual has been prepared to provide postgraduate students and researchers with a systematic, concept-oriented, and application-focused approach to the measurement and interpretation of soil physical properties.

The manual covers essential laboratory and field methods related to soil sampling, density measurements, soil texture, aggregation, soil hydraulic properties, solute transport, and soil physical quality indicators. Emphasis has been placed on clear experimental procedures, correct interpretation of results, and linkage between measurements and soil functions. The content is aligned with postgraduate curricula and competitive examinations such as ICAR– ARS and NET.

This manual is intended to serve as a comprehensive laboratory companion for students, teachers, and researchers in soil science and allied disciplines.

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CHAPTER 1

SOIL SAMPLING AND PROCESSING FOR PHYSICAL ANALYSIS (FAO, 2006)

1.1 Objectives of Soil Sampling

Soil sampling aims to collect representative soil material that accurately reflects the physical condition of a soil system under a given land use, depth, and management history. In soil physics, sampling accuracy is particularly critical because soil structure and pore continuity are highly sensitive to disturbance.

Any error introduced during sampling cannot be corrected during laboratory analysis, irrespective of analytical precision. Therefore, soil sampling constitutes the most critical step in soil physical investigations.

1.2 Principles of Representative Soil Sampling

Representative sampling requires consideration of:

- Spatial variability (slope, colour, texture)
- Land use and crop history
- Soil depth and rooting zone
- Moisture status at sampling should be avoided from:
 - Recently fertilized or irrigated spots
 - Field bunds and channels
 - Areas near trees, compost pits, wells, or roads

1.3 Depth of Sampling

Sampling depth is governed by the **zone of soil–root–water interaction** and the objective of the study.

Land Use / Crop Type	Recommended Sampling Depth
Annual field crops	0–15 cm (plough layer)
Deep-rooted crops	0–30, 30–60 cm

Orchards	0–15, 15–30, 30–45 cm
Dryland systems	Layer-wise up to rooting depth

Concept Note: In dryland and gravelly soils, subsurface layers often control water availability and must be sampled separately.

1.4 Types of Soil Samples

1. Disturbed (Bulk) Soil

Samples Used for:

- Particle density
- Particle size distribution
- Soil water diffusivity
- Solute transport experiments

These samples lose natural structure but retain mineralogical composition.

2. Undisturbed (Core) Soil

Samples Used for:

- Bulk density
- Porosity and pore-size distribution
- Hydraulic conductivity
- Moisture retention characteristics

Undisturbed samples preserve natural aggregation and pore geometry and are essential for hydraulic studies.

D. Soil Sampling Implements and Their Selection

Implement	Suitable Condition	Limitation
Tube auger	Soft, moist soil	Disturbs structure
Screw auger	Hard, dry soil	Mixing of layers
Bucket auger	Deep sampling	Ineffective in gravelly soils
Core cutter	Hydraulic studies	Not suitable for coarse fragments
Post-hole auger	Wet soils (rice fields)	Large disturbance

1.5 Soil Sampling Strategies

(i) Random Sampling

- Best for uniform, level fields
- Simple and economical
- Limited spatial coverage

(ii) Zig-Zag Sampling

- Suitable for undulating landscapes
- Better spatial representation
- Time-consuming

(iii) Latin Square Sampling

- Ideal for experimental plots
- Complete spatial coverage
- Requires careful planning

Collection of Disturbed Soil Samples

1. Select a representative sampling site avoiding bunds, channels, fertilizer bands, tree bases, and recently irrigated or disturbed locations.
2. Remove surface litter and vegetation without disturbing the soil.
3. Using a spade or auger, excavate soil up to the desired depth.
4. Collect soil from 5–10 random locations within the sampling unit.
5. Place collected soil on a clean plastic sheet and gently break large clods by hand.
6. Mix thoroughly to form a composite sample.
7. Reduce sample size using the quartering method until about 1–2 kg soil remains.
8. Transfer soil into labelled polythene bags indicating location, depth, date, and sample ID.

Processing of Disturbed Soil Samples

1. Air-dry soil samples under shade at room temperature.
2. Remove roots, stones, and organic debris manually.
3. Pass soil through an 8 mm sieve; break clods gently.
4. Record coarse fragments (>2 mm) by weight or volume.
5. Further sieve soil through a 2 mm sieve for laboratory analysis.
6. Store processed soil in airtight containers with proper labelling.

Interpretation Note: Coarse fragments must be quantified separately, especially in gravelly soils, as they strongly influence bulk density and water storage calculations.

Storage and Labelling

- Store samples in airtight, wide-mouth containers
- Label externally and internally
- Maintain a laboratory logbook with sample metadata

Collection of Undisturbed Soil Samples

1. Level the soil surface carefully without compacting.
2. Insert a core cutter vertically using steady pressure or gentle hammering.
3. Drive the cutter until the ring is fully embedded.
4. Loosen surrounding soil and extract the cutter carefully.
5. Trim excess soil flush with both ends of the ring using a knife.
6. Seal the core and transport to the laboratory with orientation marked.

Handling and Preparation of Core Samples

- Trim soil carefully without smearing
- Maintain orientation (top/bottom marked)
- Prevent moisture loss
- Store in sealed containers prior to analysis

Common Errors in Soil Sampling

- Compression during sampling
- Mixing of soil layers
- Sampling at inappropriate moisture
- Ignoring spatial variability

Applications of Proper Soil Sampling

- Reliable bulk density and porosity estimation
- Accurate soil water retention curves
- Valid hydraulic conductivity measurements
- Meaningful soil quality assessment

Viva-Voce / Concept Questions

1. Why are undisturbed samples essential for hydraulic studies?
2. How does soil moisture at sampling influence bulk density?
3. Why is gravel correction necessary in shallow soils?
4. What is the consequence of poor sampling on soil quality indices?

Reference

Food and Agriculture Organization. (2006). Guidelines for soil description (4th ed.).

FAO

CHAPTER 2

FUNDAMENTAL SOIL PHYSICAL PROPERTIES

Fundamental soil physical properties describe the basic physical constitution of soil as a porous medium composed of solids, water, and air. These properties govern the ability of soil to support plant growth, regulate the movement of water and air, and maintain structural stability under natural and managed conditions. They form the physical foundation upon which soil processes operate and strongly influence soil hydraulic behaviour, nutrient dynamics, root development, and biological activity.

Among these properties, particle density and bulk density define the mass–volume relationships of soil. Particle density represents the density of soil solids and reflects mineralogical composition, whereas bulk density includes both solids and pore spaces and serves as a sensitive indicator of soil compaction, porosity, and structural condition. Variations in bulk density directly affect root penetration, aeration, and water movement, linking it closely to soil productivity and management practices.

Particle size distribution, expressed as soil texture, describes the relative proportions of sand, silt, and clay. Texture is a permanent soil property that controls pore-size distribution, water retention, permeability, and susceptibility to erosion. Coarse-textured soils drain rapidly with low water-holding capacity, while fine-textured soils retain more water but may restrict aeration. Loamy soils generally provide a favourable balance between retention and transmission.

Soil aggregation and structural stability arise from the organization of primary particles into aggregates. Aggregate stability influences infiltration, erosion resistance, surface crusting and protection of organic carbon and is strongly affected by organic matter, biological activity, and management practices.

This chapter deals with four core properties:

- Particle density
- Bulk density
- Particle size distribution (soil texture)
- Soil aggregate stability

Together, these parameters define the soil's physical framework.

2.1 PARTICLE DENSITY OF SOIL (Blake and Hartge, 1986)

Measurement of soil particle density requires careful preparation of oven-dry soil, accurate weighing, and complete removal of entrapped air to ensure reliable results. Since particle density represents the mass of soil solids per unit volume, it is essential that soil aggregates are fully dispersed and that air bubbles are eliminated during water displacement in the pycnometer. The use of air-free distilled water and proper temperature control are critical, as errors in volume determination directly affect the calculated particle density. Accurate measurement of particle density is important because it serves as a reference for estimating soil porosity and interpreting soil physical behaviour.

Principle

Particle density is determined using Archimedes' principle, which states that the volume of soil solids equals the volume of liquid displaced when soil is immersed in a fluid. A pycnometer of known volume is used to quantify this displacement.

Apparatus

- Pycnometer with stopper
- Analytical balance (± 0.01 g)
- Oven (105 ± 2 °C)
- Air-free distilled water
- Beaker, funnel, glass rod

Procedure

1. Clean and dry the pycnometer; weigh it empty.
2. Add 10 g oven-dry soil to the pycnometer and record weight.
3. Add air-free distilled water to two-thirds volume.
4. Remove entrapped air by gentle boiling or shaking.
5. Fill pycnometer completely with air-free water and insert stopper.

6. Wipe dry and weigh pycnometer with soil and water.
7. Fill pycnometer with water alone and record weight.
8. Calculate particle density using standard formula.

Calculation

$$\rho_s = \frac{W_s}{(W_{pw} + W_s - W_{psw})}$$

Where:

ρ_s = Particle density of soil (g cm⁻³ or Mg m⁻³)

W_s = Weight of oven-dry soil taken in the pycnometer (g)

W_{pw} = Weight of the pycnometer completely filled with water (g)

W_{psw} = Weight of the pycnometer containing soil and water (g)

Interpretation

- Typical mineral soils: 2.60–2.75 Mg m⁻³
- Lower values indicate higher organic matter content
- Higher values suggest dominance of Fe-oxide or heavy minerals

Concept Link: Errors in particle density propagate directly into porosity estimates.

Viva-Voce Questions

1. Why is particle density less variable than bulk density?
2. Why is organic matter removal sometimes avoided?

References

1. Blake, G.R., & Hartge, K.H. (1986). Particle density. In *Methods of Soil Analysis, Part 1*. ASA–SSSA

2.2 BULK DENSITY OF SOIL (Blake and Hartge, 1986)

Measurement of soil bulk density requires careful collection of undisturbed soil samples, accurate determination of sample volume, and precise drying and weighing procedures to

ensure reliable results. Since bulk density is highly sensitive to soil compaction, structure, and moisture status at the time of sampling, the core sampler must be inserted gently to avoid compression or disturbance of the soil. Proper trimming of excess soil, prevention of moisture loss during handling, and complete oven drying to constant weight are essential. Any error introduced during sampling or volume measurement directly affects the calculated bulk density and may lead to incorrect interpretation of soil physical condition and root growth limitations.

Principle

An undisturbed soil core of known volume is extracted and dried to constant weight. Bulk density is calculated as the ratio of oven-dry mass to core volume.

Apparatus

1. Core sampler (core cutter assembly)
 - Cylindrical metal sampler with cutting edge
 - Usually made of steel or brass
2. Metal soil cores (rings)
 - Known internal diameter and height
 - Common sizes:
 - 5–7 cm diameter
 - 5–15 cm height
3. Driving head / hammer
 - For inserting the core sampler into soil
4. Aluminium moisture cans or metal containers
 - For holding soil cores during weighing and drying
5. Sharp knife or spatula
 - For trimming excess soil flush with core edges
6. Vernier caliper or measuring scale

- To measure internal diameter and height of the core accurately
7. Hot air oven
 - Maintained at 105 ± 2 °C
 - For drying soil to constant weight
 8. Analytical or top-pan balance
 - Accuracy: ± 0.01 g
 - For weighing moist and oven-dry soil
 9. Desiccator
 - Containing silica gel or CaCl_2
 - For cooling samples after oven drying
 10. Plastic bags or sealing material
 - To prevent moisture loss during transport from field to laboratory

Procedure

1. Measure internal diameter and height of the core.
2. Weigh core with moist soil.
3. Dry soil at 105 °C until constant weight (24-48 h).
4. Cool in desiccator and record dry weight.
5. Calculate bulk density as oven-dry mass divided by core volume.

Calculation

$$\text{Bulk Density} = \frac{W_{\circ d}}{V}$$

where:

- BD=Bulk density (g cm^{-3} or Mg m^{-3})
- $W_{\circ d}$ =Oven-dry weight of soil (g)
- V=Volume of soil core (cm^3)

Volume of Soil Core

$$V = \pi r^2 h$$

or

$$V = \frac{\pi d^2 h}{4}$$

where:

r = Radius of core (cm)

d = Internal diameter of core (cm)

h = Height (length) of core (cm)

Interpretation Guidelines

Texture	Critical Bulk Density (Mg m^{-3})
Sandy soils	>1.75
Loamy soils	>1.65
Clayey soils	>1.55

Interpretation Note: Values exceeding these limits restrict root elongation and water movement.

Applications

- Soil compaction diagnosis
- Porosity estimation
- Input for water balance models
- Soil quality assessment

Viva-Voce Questions

1. Why does bulk density usually increase with depth?
2. Why is bulk density lower in organic soils?

References

1. Blake, G.R., & Hartge, K.H. (1986). Bulk density. DOI: <https://doi.org/10.2136/sssabookser5.1.2ed.c13>

2.3 DETERMINATION OF SOIL PARTICLE SIZE DISTRIBUTION

(Gee and Bauder, 1986)

Particle size distribution (PSD), commonly referred to as soil texture, describes the relative proportions of sand, silt, and clay in a soil. It is a fundamental and nearly permanent soil property that strongly influences soil physical behavior. Soil texture governs pore-size distribution, which in turn controls water retention, hydraulic conductivity, aeration, infiltration, and susceptibility to erosion. It also affects nutrient holding capacity, root penetration, and soil workability. Accurate determination of PSD is therefore essential for interpreting soil hydraulic properties, predicting water and solute movement, classifying soils, and making sound decisions related to irrigation management, soil conservation, and sustainable land use planning.

Aim

To determine the particle size distribution (sand, silt, and clay) of a soil sample and to classify the soil textural class using the International Pipette Method and the Hydrometer Method.

Principle

Particle size distribution analysis is based on the dispersion of soil aggregates into primary particles followed by separation of particles according to their settling velocity in water, as governed by Stokes' law. Larger particles settle faster than smaller particles. By measuring the concentration of particles remaining in suspension at a given depth and time, the proportions of sand, silt, and clay can be quantified.

$$v = \frac{2}{9} \cdot \frac{r^2 (\rho_p - \rho_f) g}{\mu}$$

Where,

μ - Terminal settling velocity (m s⁻¹)

r- Radius of particle (m)

ρ_p - Density of particle (kg m⁻³)

ρ_f - Density of fluid (kg m⁻³)

g- Acceleration due to gravity (m s⁻²)

μ - Dynamic viscosity of fluid (Pa·s (kg m⁻¹ s⁻¹))

2.3.1 INTERNATIONAL (MECHANICAL) PIPETTE METHOD

Apparatus and Reagents

- Analytical balance
- 2 mm sieve
- 500 ml beaker
- Hot water bath
- Mechanical stirrer
- Sedimentation cylinder (1000 ml)
- Pipette (10 ml)
- Stopwatch
- Oven (105 ± 2 °C)
- Sodium hexametaphosphate (dispersing agent, 5%)
- Hydrogen peroxide (H₂O₂, 6%)
- Distilled water

Procedure

1. Air-dry the soil sample and pass it through a 2 mm sieve.
2. Weigh 50 g of soil into a beaker.
3. Add 6% H₂O₂ (50 ml) gradually to remove organic matter and heat gently until effervescence ceases.
4. Cool the sample and wash to remove excess peroxide.
5. Add 100 ml of 5% sodium hexametaphosphate as a dispersing agent.
6. Transfer the suspension into a mechanical stirrer and stir for 10 minutes.
7. Transfer the dispersed suspension into a 1000 ml sedimentation cylinder and make the volume up to the mark with distilled water.
8. Stopper the cylinder and shake vigorously; note the starting time.

9. Withdraw 10 ml aliquots using a pipette from a fixed depth (usually 10 cm) at specified settling times.
10. Transfer the aliquot to a moisture can, dry at 105 °C, and weigh.
11. Repeat for required time intervals to determine silt + clay and clay fractions.

Observations

Sampling depth (cm)	Time after shaking	Aliquot volume (ml)	Oven-dry weight of soil in aliquot (g)
10 cm	45 s (USDA: <50 μm)	10	$W_{50} =$
10 cm	4 min 38 s (ISSS: <20 μm)	10	$W_{20} =$
10 cm	7 h 45 min (<2 μm, clay)	10	$W_2 =$

Calculations

$$\text{Silt + Clay (\%)} = \frac{W_{50} \times 1000}{10 \times W_{od}} \times 100$$

$$\text{Clay (\%)} = \frac{W_2 \times 1000}{10 \times W_{od}} \times 100$$

$$\text{Sand (\%)} = 100 - (\text{Silt} + \text{Clay})$$

$$\text{Silt (\%)} = (\text{Silt} + \text{Clay}) - \text{Clay}$$

Where;

W_{50} , $W_2 =$ oven-dry weight of particles <50 μm and <2 μm

$W_{od} =$ oven-dry weight of soil taken

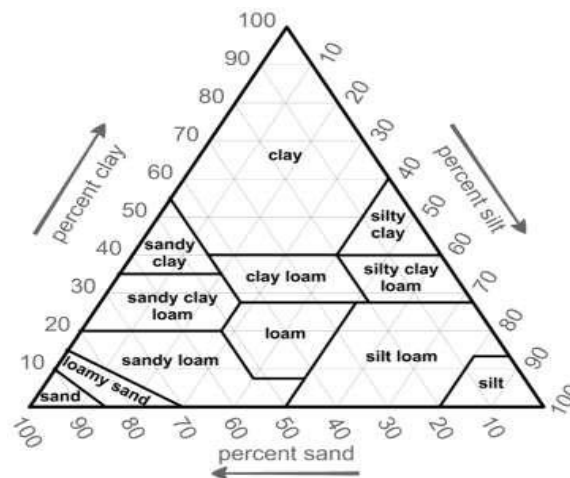


Fig. USDA soil textural triangle showing the classification of soils into twelve textural classes based on relative percentages of sand (0.05–2.0 mm), silt (0.002–0.05 mm), and clay (<0.002 mm). (Source: United States Department of Agriculture).

Result

The soil contains ___% sand, ___% silt, and ___% clay and is classified as _____ textural class.

HYDROMETER METHOD (BOUYOCOS METHOD)

Apparatus and Reagents

- Hydrometer (Bouyoucos type)
- Sedimentation cylinder (1000 ml)
- Mechanical stirrer
- Thermometer
- Stopwatch
- Oven (105 ± 2 °C)
- Sodium hexametaphosphate
- Hydrogen peroxide (6%)
- Distilled water

Procedure

1. Pass air-dried soil through a 2 mm sieve and weigh 50 g soil.
2. Treat with 6% H₂O₂ to remove organic matter (50 ml)
3. Add sodium hexametaphosphate (100ml) and stir mechanically for 10 minutes.
4. Transfer the suspension to a 1000 ml cylinder and make volume.
5. Shake the cylinder vigorously and place it on a level surface; start timing.
6. Insert the hydrometer gently and record the reading at 40 seconds.
7. Note the temperature of suspension.
8. Take a second hydrometer reading after 2 hours.
9. Apply temperature and blank corrections to the readings.

Observations

Observation	Time after shaking	Hydrometer reading	Temperature (°C)	Corrected reading*
1	40 seconds	R _{40s}		R _{40s} *
2	2 hours	R _{2h}		R _{2h} *

Calculations

$$\text{Silt + Clay (\%)} = \frac{R_{40s} - R_b}{W} \times 100$$

$$\text{Clay (\%)} = \frac{R_{2h} - R_b}{W} \times 100$$

$$\text{Sand (\%)} = 100 - (\text{Silt} + \text{Clay})$$

$$\text{Silt (\%)} = (\text{Silt} + \text{Clay}) - \text{Clay}$$

where:

R_{40s} = hydrometer reading at 40 s

R_{2h} = hydrometer reading at 2 h

R_b = blank reading

W = weight of soil (g)

Result

The soil is classified as _____ textural class based on USDA/ISSS textural triangle.

Precautions

- Ensure complete dispersion of soil aggregates.
- Avoid air bubbles while taking hydrometer readings.
- Maintain constant temperature conditions.
- Handle H₂O₂ carefully to avoid burns.

Viva-Voce / Exam Questions

1. Why is dispersion necessary before PSD analysis?
2. Why is Stokes' law only approximately valid for soil particles?
3. Difference between pipette and hydrometer methods?
4. Why is texture considered a permanent soil property?

References

Gee, G. W., & Bauder, J. W. (1986). Particle-size analysis. *Methods of soil analysis: Part 1 Physical and mineralogical methods*, 5, 383-411.

2.4 SOIL AGGREGATE STABILITY

Soil aggregate stability measurement provides a quantitative framework for evaluating the resistance of soil structure to disruptive forces such as rainfall impact, wetting–drying cycles, wind action, and mechanical disturbance. Aggregates represent the fundamental structural units of soil, formed through the binding of primary particles by organic matter, microbial products, roots, and inorganic cementing agents. The stability of these aggregates governs key soil functions including infiltration, aeration, erosion resistance, and protection of soil organic carbon. Consequently, aggregate stability is widely recognized as a core indicator of soil physical quality.

Because soil structure responds dynamically to land use, management practices, and environmental stress, no single measurement adequately captures aggregate behavior under all conditions. Therefore, soil aggregate stability is assessed using multiple complementary indices, each reflecting a distinct aspect of structural integrity.

Dry aggregate size

distribution, obtained through dry sieving, evaluates the resistance of aggregates to mechanical forces and is particularly relevant for understanding soil behavior under tillage and wind erosion. In contrast, wet aggregate stability, determined by wet sieving methods, assesses the susceptibility of aggregates to slaking and dispersion upon wetting, closely simulating rainfall-induced breakdown and water erosion processes.

Quantitative indices such as Water-Stable Aggregates (WSA), Mean Weight Diameter (MWD), and Geometric Mean Diameter (GMD) are commonly used to integrate aggregate size distributions into interpretable metrics. Higher values of these indices indicate greater structural stability, improved pore continuity, and enhanced resilience to physical degradation. These indices are especially useful for comparing soils across land uses, management systems, and soil depths. When interpreted alongside supporting properties such as soil organic carbon, bulk density, and texture, aggregate stability indices provide mechanistic insight into soil degradation and restoration processes. Thus, the use of multiple aggregate stability indices enables a robust and functionally

meaningful assessment of soil structural health.

2.4.1 MEASUREMENT OF DRY AGGREGATE STABILITY BY DRY SIEVING METHOD (Kemper and Rosenau, 1986)

Aim

To determine the size distribution and stability of dry soil aggregates using the dry sieving method.

Principle

Dry aggregate stability represents the resistance of soil aggregates to mechanical breakdown under dry conditions, simulating the disruptive forces of wind and tillage. When air-dry soil is subjected to mechanical shaking through a nest of sieves, aggregates are separated based on their size. The proportion of aggregates retained on different sieves reflects soil structural stability under dry conditions.

Apparatus Required

- Rotary sieve shaker or manual sieve set
- Set of sieves (e.g., 5, 2, 1, 0.5, 0.25 mm)
- Balance (± 0.01 g)
- Oven (105 ± 2 °C)
- Sample trays
- Brush

Procedure

1. Collect soil samples when soil is reasonably dry.
2. Air-dry the soil at room temperature under shade.
3. Gently break large clods along natural cleavage planes without crushing aggregates.
4. Weigh a known amount of soil sample (usually 100 g).
5. Arrange the sieves in descending order of mesh size.
6. Place soil on the top sieve and fix the lid.

7. Shake the sieve set mechanically for 20 minutes (or manually with uniform tapping).
8. Carefully remove each sieve and collect soil retained on each.
9. Weigh the soil retained on each sieve.
10. Oven-dry subsamples to correct weights to oven-dry basis.

Observation Table – Dry Aggregate Stability

Sieve size (mm)	Weight of aggregates retained (g)	Oven-dry weight (g)	% aggregates retained
>5.0			
5.0 – 2.0			
2.0 – 1.0			
1.0 – 0.5			
0.5 – 0.25			
<0.25			
Total			100

Calculation

$$\% \text{ Aggregates in each size class} = \frac{\text{Weight retained on sieve}}{\text{Total oven-dry soil weight}} \times 100$$

Result

The dry aggregate size distribution of the soil indicates _____ stability under dry conditions.

References

Kemper, W.D., & Rosenau, R.C. (1986). Aggregate stability and size distribution.
DOI: <https://doi.org/10.2136/sssabookser5.1.2ed.c17>

2.4.2 MEASUREMENT OF WET AGGREGATE STABILITY BY WET SIEVING (Yoder, 1936)

Aim

To determine the stability of soil aggregates against water-induced breakdown using the wet sieving method.

Principle

Wet aggregate stability measures the resistance of soil aggregates to slaking and dispersion when wetted, simulating rainfall impact. Aggregates stable in water indicate good soil structure, high organic matter, and resistance to erosion. The proportion of water-stable aggregates (WSA) is a key indicator of soil physical quality.

Apparatus Required

- Yoder type wet sieve apparatus
- Set of sieves (5, 2, 1, 0.5, 0.25 mm)
- Balance (± 0.01 g)
- Oven (105 ± 2 °C)
- Beakers
- Hydrogen peroxide (H_2O_2)
- Dispersing agent

Procedure

1. Take 50 g air-dry aggregates (5–8 mm size).
2. Place aggregates gently on the top sieve.
3. Slowly raise water level to wet aggregates and allow pre-wetting for 10 minutes.
4. Oscillate the sieves vertically in water at 30 cycles per minute for 10 minutes.
5. Remove sieves and allow excess water to drain.
6. Transfer aggregates retained on each sieve to labeled beakers.
7. Oven-dry at 105 °C for 24 hours and weigh.
8. To correct for sand content, disperse aggregates using H_2O_2 and dispersant.
9. Wash dispersed soil through the same sieves.
10. Oven-dry and weigh primary particles retained on each sieve.

Table . Observations**(A) Oven-dry mass of aggregates**

Sieve size (mm)	Weight of aggregates (g)
>5.0	
5.0 – 2.0	
2.0 – 1.0	
1.0 – 0.5	
0.5 – 0.25	
<0.25	
Total (M ₀)	

(B) Oven-dry mass of primary particles (after dispersion)

Sieve size (mm)	Weight of primary particles (g)
>5.0	
5.0 – 2.0	
2.0 – 1.0	
1.0 – 0.5	
0.5 – 0.25	

Calculations

1. Water Stable Aggregates (WSA, %)

$$\% \text{ WSA}(> 0.25 \text{ mm}) = \frac{\sum(M_i - P_i)}{M_0} \times 100$$

Where,

M_i = mass of aggregates retained on each sieve

P_i = mass of primary particles

M_0 = total mass of aggregates

2. Mean Weight Diameter (MWD)

$$\text{MWD} = \sum(X_i \times W_i)$$

Where,

X_i = mean diameter of size class (mm)

W_i = proportion of aggregates in that size class

Result

The percentage of water-stable aggregates and MWD indicate that the soil has _____ aggregate stability.

Precautions

- Avoid sudden wetting of aggregates.
- Maintain uniform oscillation rate.
- Correct for sand content.
- Handle aggregates gently to avoid artificial breakdown.

Applications

- Assessment of soil structural stability
- Erosion risk evaluation
- Soil quality and conservation studies
- Impact assessment of organic amendments and tillage

Viva-Voce / Exam Questions

1. Why is wet aggregate stability more important than dry stability?
2. How does organic matter influence aggregation?
3. What is the significance of MWD?
4. Difference between slaking and dispersion?

References

Yoder, R. E. (1936). A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses.

CHAPTER 3

SOIL HYDRAULIC PROPERTIES

Soil hydraulic properties describe the ability of soil to retain, transmit, and release water under different energy states, thereby controlling the movement, storage, and availability of water within the soil profile. These properties regulate soil–water–plant–atmosphere interactions and are fundamental to improving irrigation efficiency, enhancing drought resilience, reducing nutrient losses, and sustaining crop productivity across diverse agroecosystems. Understanding soil hydraulic behaviour is therefore central to both agricultural management and environmental protection.

The hydraulic behaviour of soil is governed primarily by pore size distribution, continuity, and connectivity, which determine how easily water enters, moves through, and is retained within the soil matrix. These pore characteristics are strongly influenced by soil texture, structure, organic matter content, and degree of compaction. Coarse-textured soils dominated by macropores generally exhibit rapid infiltration and drainage but have limited capacity to retain water against gravity. In contrast, fine-textured soils contain a greater proportion of micropores that store larger amounts of water, although much of this water may be held at high suction and thus be less available to plants. Soil aggregation and structural stability play a critical role in maintaining continuous transmission pores, while compaction caused by machinery traffic or improper management reduces macroporosity, restricts water movement, and impairs root growth.

Because pore geometry and continuity are highly sensitive to land use and management practices, soil hydraulic properties exhibit considerable spatial and temporal variability. Tillage intensity, residue management, organic amendments, cropping systems, and land use change can significantly modify infiltration, water retention, and hydraulic conductivity. This chapter focuses on the measurement and interpretation of key soil hydraulic properties that collectively describe soil water dynamics. These include soil moisture content, soil water potential (particularly matric potential), the soil moisture characteristic curve, saturation and water holding capacity, hydraulic conductivity, and infiltration rate. Together, these properties provide an integrated understanding of how soils store, transmit, and supply water to plants under varying environmental and management conditions, forming the basis for informed irrigation planning, soil and

water conservation, and sustainable land management.

3.1 SOIL MOISTURE CONTENT BY GRAVIMETRIC METHOD

(Klute, 1986)

Background and Significance

Soil moisture content represents the quantity of water present in the soil at a given time. It is the most basic hydraulic parameter and serves as the reference for all other soil water measurements. However, moisture content alone does not describe water availability unless interpreted in conjunction with soil water potential.

Gravimetric determination is considered the reference (standard) method against which all indirect methods are calibrated.

Principle

When moist soil is heated at 105 °C, water held in soil pores evaporates, resulting in a reduction in soil mass. The loss in mass is assumed to be equal to the mass of water originally present in the soil.

Apparatus Required

1. Soil auger or sampling tool
 - For collecting soil samples from the desired depth
2. Aluminium moisture cans with tight-fitting lids
 - To store and dry soil samples without moisture loss
3. Analytical balance or top-pan balance
 - Accuracy of at least ± 0.01 g
4. Hot air oven
 - Maintained at 105 ± 2 °C for oven drying of soil
5. Desiccator
 - Containing silica gel or calcium chloride
 - For cooling samples after drying

6. Forceps or tongs
 - For handling hot moisture cans safely
7. Marker pen and labels
 - For proper identification of samples

Procedure

1. Select a representative site and collect soil samples from the desired depth using a suitable auger or sampler.
2. Immediately transfer the moist soil into a pre-weighed aluminium moisture can fitted with a tight lid to prevent moisture loss.
3. Record the weight of the can containing moist soil as soon as possible after sampling.
4. Remove the lid and place the moisture can with soil in a hot air oven maintained at 105 ± 2 °C.
5. Dry the soil for 24–48 hours or until a constant weight is obtained, indicating complete removal of soil water.
6. After drying, remove the can from the oven and immediately cover it with the lid to prevent absorption of atmospheric moisture.
7. Allow the can to cool in a desiccator containing a suitable drying agent such as silica gel or calcium chloride.
8. Weigh the can containing oven-dry soil accurately using an analytical balance.
9. Record the weight of the empty moisture can separately.
10. Calculate the gravimetric moisture content of the soil using the difference between moist and oven-dry weights.

Calculations

Gravimetric moisture content:

$$\theta_w = \frac{W_w}{W_{od}} \times 100$$

Volumetric moisture content: $\theta_v = \theta_w \times \rho_b$

Interpretation

Sandy soils generally exhibit low soil moisture content due to their large pore sizes, but they allow rapid drainage of water. Clay soils retain comparatively higher amounts of moisture because of their fine pore structure; however, a significant portion of this water is held at high suction and is therefore less available to plants. Volumetric moisture content provides a more meaningful representation of soil water status, as it integrates gravimetric moisture with soil bulk density.

Limitations

The gravimetric method is destructive in nature, as soil samples must be removed and oven-dried for analysis. It is also time-consuming because it requires prolonged drying to achieve constant weight. In addition, this method provides information only on the quantity of soil water and does not indicate the energy status or availability of water to plants.

Viva-Voce Questions

Why is gravimetric moisture considered a reference method?

Why does equal moisture content not imply equal water availability?

References

Klute, A. (Ed.). (1986). Methods of soil analysis. Part 1. Physical and mineralogical methods (No. Ed. 2, pp. 1188-pp)

3.2 SOIL MOISTURE CONTENT BY NEUTRON PROBE METHOD (INTERNATIONAL ATOMIC ENERGY AGENCY, 1970)

The neutron probe is an important tool for the measurement of soil moisture because it enables rapid, non-destructive, and repeated assessment of soil water content over time at the same location. Unlike the gravimetric method, which requires destructive sampling, the neutron probe allows continuous monitoring of soil moisture dynamics throughout the crop growth period, making it particularly valuable for irrigation scheduling and soil water balance studies. Its ability to measure moisture at multiple depths provides a

reliable representation of profile soil water distribution, which is critical for understanding root water uptake and deep percolation losses.

The technique is especially useful in research and large-scale field studies where frequent measurements are required without disturbing soil structure. By integrating soil moisture measurements across depths, the neutron probe supports accurate estimation of crop water use and irrigation efficiency. Although careful calibration and radiation safety precautions are essential, the neutron probe remains a benchmark method for subsurface soil moisture measurement, particularly in long-term experiments and hydrological investigations.

Aim

To determine the volumetric soil moisture content at different soil depths using the neutron probe (neutron moisture meter) method.

Principle

The neutron probe method is based on the principle that fast neutrons are slowed down (thermalized) primarily by hydrogen atoms, which are abundantly present in soil water. A radioactive source (usually Americium–Beryllium) emits fast neutrons that collide elastically with hydrogen nuclei in the soil, losing energy in the process. The number of slowed (thermal) neutrons detected by the probe is proportional to the amount of water present in the soil.

The detected neutron count is converted to volumetric soil moisture content using a calibration relationship developed specifically for the soil under study.

Apparatus Required

- Neutron moisture meter (probe and scaler/rate meter)
- Radioactive neutron source (Am–Be or Ra–Be)
- Aluminium or PVC access tubes
- Soil auger
- Hammer or insertion tool
- Moisture cans

- Oven (105 ± 2 °C)
- Balance (± 0.01 g accuracy)
- Stopwatch
- Radiation safety accessories (source shield, warning signs)

Installation of Access Tube

1. Drill a vertical hole in the soil using a soil auger to the desired depth.
2. Insert the access tube carefully into the hole, ensuring intimate contact between soil and tube wall.
3. Plug the lower end of the tube to prevent water entry.
4. Leave the top end of the tube a few centimetres above the soil surface and cover it to prevent debris entry.
5. Allow the soil around the tube to stabilize before taking measurements.

Procedure

1. Switch on the neutron moisture meter and allow it to stabilize as per manufacturer instructions.
2. Take a standard count by placing the probe in the shielding container and record the count.
3. Lower the probe into the access tube to the desired depth and lock it in position.
4. Record the observed neutron count for a fixed counting time (e.g., 16 or 32 seconds).
5. Repeat measurements at different depths as required.
6. Calculate the count ratio (CR) for each depth.
7. Using the soil-specific calibration curve, determine the volumetric soil moisture content corresponding to the count ratio.

Table. Observations

Depth (cm)	Standard count	Observed count	Count ratio (CR)	Volumetric moisture ($\text{cm}^3 \text{cm}^{-3}$)
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Calculations

1. Count Ratio

$$\text{Count Ratio (CR)} = \frac{\text{Observed Count}}{\text{Standard Count}}$$

2. Volumetric Soil Moisture Content:

$$\theta_v = a + b(\text{CR})$$

where:

θ_v = volumetric soil moisture content ($\text{cm}^3 \text{ cm}^{-3}$)

a, b = calibration constants obtained experimentally

Calibration of Neutron Probe

1. Collect undisturbed soil samples from the same depths using a core sampler.
2. Determine volumetric moisture content gravimetrically.
3. Plot volumetric moisture content against count ratio.
4. Develop a regression equation to obtain calibration constants.

Result

The volumetric soil moisture content at different depths was determined using the neutron probe method and ranged from ____ to _____ $\text{cm}^3 \text{ cm}^{-3}$.

Interpretation

- Higher count ratios indicate higher soil moisture content.
- Neutron probe is highly suitable for profile soil moisture monitoring.
- Accuracy improves with proper soil-specific calibration.

Precautions

- Do not use the neutron probe near the soil surface (top 10–15 cm).
- Ensure access tubes are straight and undamaged.
- Follow radiation safety guidelines strictly.
- Avoid measurements immediately after heavy rainfall or irrigation.

Advantages

- Non-destructive method
- Suitable for repeated measurements
- Effective for deep soil moisture monitoring

Limitations

- Radiation hazard
- Requires soil-specific calibration
- Not suitable for shallow soil layers

Applications

Neutron probe measurements are widely used in irrigation scheduling, soil water balance studies, crop water use estimation, and hydrological research.

Viva-Voce / Exam Questions

1. Why is hydrogen the key element in neutron probe measurements?
2. Why is calibration soil-specific?
3. Why should neutron probes not be used for surface soil?
4. Difference between neutron probe and TDR methods?

References

International Atomic Energy Agency. (1970). Neutron moisture gauges: A guidebook on theory and practice. Vienna, Austria: International Atomic Energy Agency.

3.3 SOIL MOISTURE CONTENT BY TIME DOMAIN REFLECTOMETRY – TDR (Topp et al., 1980)

The measurement of soil moisture content using Time Domain Reflectometry (TDR) represents a modern, non-destructive, and precise approach for quantifying volumetric water content in soils. Unlike conventional gravimetric methods, TDR enables rapid and repeated measurements at the same location, thereby capturing temporal variations in soil moisture with minimal disturbance to the soil structure. The technique is based on robust physical principles linking the dielectric properties of soil to its water content, making it highly suitable for both laboratory and field applications. Owing to the absence of radiation hazards and its applicability across a wide range of soil textures and depths, TDR has become an important tool in soil physics, irrigation management, and hydrological studies. Accurate application of this method requires careful probe installation, appropriate calibration, and systematic data interpretation to ensure reliable estimation of soil moisture status.

Aim

To determine the volumetric soil moisture content using the Time Domain Reflectometry (TDR) technique.

Principle

Time Domain Reflectometry is based on the measurement of the dielectric constant (K) of soil, which strongly depends on its water content. Water has a very high dielectric constant (~ 81) compared to soil solids (4–8) and air (≈ 1). As soil water content increases, the bulk dielectric constant of soil also increases. In the TDR method, a high-frequency electromagnetic pulse is transmitted along metal rods inserted into the soil. The pulse is reflected back from the end of the rods, and the travel time of the pulse is measured. This travel time is directly related to the dielectric constant of the soil, which is then empirically related to volumetric soil moisture content.

Apparatus Required

- Time Domain Reflectometry (TDR) instrument
- TDR probe (two- or three-rod stainless steel probe of known length)

- Coaxial cable
- Soil auger or probe insertion tool
- Measuring scale
- Data logger or display unit (if separate)

Procedure

1. Select a representative soil site free from stones, roots, and cracks.
2. If required, prepare a small pilot hole to facilitate probe insertion without bending the rods.
3. Insert the TDR probe vertically or horizontally into the soil to the desired depth, ensuring firm contact between soil and probe rods and avoiding air gaps.
4. Connect the probe to the TDR instrument using a coaxial cable.
5. Switch on the TDR unit and allow it to stabilize.
6. Initiate the measurement to transmit the electromagnetic pulse through the probe rods.
7. Record the travel time (t) of the pulse or the displayed dielectric constant value.
8. Repeat measurements at multiple locations or depths to account for spatial variability.
9. If soil-specific calibration is available, apply the calibration equation to convert dielectric constant into volumetric moisture content.

Table. Observations

Depth (cm)	Travel time (ns) / Dielectric constant (K)	Volumetric moisture content (cm ³ cm ⁻³)

Calculations

Dielectric Constant : $K = \left(\frac{ct}{2L}\right)^2$

Where,

K = Dielectric constant of soil

C = Velocity of light (3×10^8 m s⁻¹)

t = Travel time of electromagnetic pulse (s)

L = Length of TDR probe (m)

Volumetric Soil Moisture Content

Using the widely accepted Topp et al. (1980) relationship:

$$\theta_v = -0.053 + 0.0292K - 0.00055K^2 + 0.0000043K^3$$

where:

θ_v = Volumetric soil moisture content ($\text{cm}^3 \text{cm}^{-3}$)

K = Dielectric constant of soil

Result

The volumetric soil moisture content of the given soil sample was found to be _____ $\text{cm}^3 \text{cm}^{-3}$ using the TDR method.

Interpretation

- Higher dielectric constant indicates higher soil moisture content.
- TDR provides direct measurement of volumetric moisture content.
- Results are reliable over a wide range of soil textures when proper calibration is used.

Advantages

- Non-destructive and rapid
- No radiation hazard
- Suitable for surface and subsurface soils
- Allows repeated measurements at the same location

Limitations / Sources of Error

- Air gaps around probes cause underestimation
- Salinity and temperature variations may affect readings
- Requires careful probe installation and calibration

Precautions

- Ensure good soil–probe contact.
- Avoid bending or damaging probe rods.
- Do not insert probes into very stony soils.
- Use soil-specific calibration for high accuracy.

Applications

TDR is widely used in irrigation scheduling, soil water balance studies, hydrological modelling, and monitoring soil moisture dynamics under different land use and management systems.

Viva-Voce / Exam Questions

1. Why does soil water content strongly influence dielectric constant?
2. How does soil salinity affect TDR measurements?
3. Why is TDR preferred over neutron probe in surface soils?
4. Difference between gravimetric and TDR methods?

References

Topp, G. C., Davis, J. L., & Annan, A. P. (1980). Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. *Water Resources Research*, 16(3), 574–582. <https://doi.org/10.1029/WR016i003p00574>

3.4 MEASUREMENT OF SOIL MATRIC POTENTIAL USING TENSIO METER (Stolte, 1997)

Measurement of soil matric potential using a tensiometer requires careful preparation, proper installation, and adequate equilibration time to ensure reliable readings. Since the instrument operates on the principle of hydraulic continuity between soil water and the water-filled tensiometer, complete removal of air from the system and intimate contact between the ceramic cup and surrounding soil are essential. Tensiometers function effectively only in the wet to moderately moist range of soil water status, and therefore

measurements should be planned accordingly. Accurate setting and handling of the tensiometer are critical, as improper installation or trapped air can lead to erroneous estimation of soil water suction and misinterpretation of soil water availability.

Aim

To measure the soil matric potential (soil water suction) at a specified depth using a tensiometer.

Principle

Soil matric potential represents the energy status of water held in soil due to capillary and adsorptive forces. A tensiometer measures matric potential by allowing water to move between the soil and a porous ceramic cup attached to a water-filled tube. When the surrounding soil is unsaturated, water moves out of the tensiometer, creating a negative pressure (suction) inside the tube. This suction is measured using a vacuum gauge or mercury manometer and represents the soil matric potential at the depth of installation. Tensiometers are effective in the wet range of soil moisture, typically from 0 to about -80 kPa.

Apparatus Required

- Tensiometer (gauge type or mercury manometer type)
- Porous ceramic cup
- Vacuum gauge or Hg–H₂O manometer
- De-aired (boiled and cooled) distilled water
- Soil auger or rod for making installation hole
- Rubber stopper or septum
- Measuring scale or ruler

Procedure

1. Immerse the ceramic cup of the tensiometer in de-aired water for **24–48 hours** to ensure complete saturation.
2. Fill the tensiometer tube completely with de-aired water, ensuring that no air bubbles remain inside the tube or ceramic cup.
3. Seal the tensiometer tightly with a stopper or septum.

4. Using a soil auger, make a hole in the soil up to the desired depth where matric potential is to be measured.
5. Insert the tensiometer vertically into the hole so that the ceramic cup makes firm contact with the surrounding soil.
6. Pack soil gently around the tensiometer to ensure proper soil–cup contact and prevent air entry.
7. Allow the tensiometer to equilibrate with the soil for sufficient time (usually 1–2 hours in moist soils).
8. Record the vacuum gauge reading or mercury rise in the manometer once the reading stabilizes.
9. Repeat measurements at regular intervals, if required, to monitor changes in soil matric potential.

Observations

Depth of tensiometer (cm)	Gauge reading (centibar or cm Hg)	Date and time

Calculations

(A) Gauge Type Tensiometer

$$h = -10R + Z$$

Where,

h = Soil matric potential (cm of water)

R = Gauge reading (centibar)

Z = Depth of ceramic cup below soil surface (cm)

$$1 \text{ centibar} = 1 \text{ kPa}$$

(B) Mercury Manometer Type

$$h = -12.6Z_1 + Z_2 + Z_3$$

where,

Z_1 = Height of mercury rise (cm)

Z_2 = Height of mercury reservoir above soil surface (cm)

Z_3 = Depth of ceramic cup below soil surface (cm)

Result

The soil matric potential at a depth of _____ cm was found to be _____ kPa (or cm of water).

Interpretation

- Low suction values indicate wet soil conditions with readily available water.
- High suction values indicate drying soil and increasing water stress for plants.
- Tensiometer readings are most useful for irrigation scheduling in the root zone.

Precautions

- Ensure complete removal of air bubbles from the tensiometer.
- Maintain good contact between ceramic cup and soil.
- Do not use tensiometers in very dry soils beyond their operational range.
- Protect tensiometers from temperature fluctuations and direct sunlight.

Applications

Measurement of soil matric potential using a tensiometer is widely used for irrigation scheduling, studying soil water movement, assessing root zone water availability, and evaluating soil hydraulic behavior under field conditions.

Viva-Voce / Exam Questions

1. What is soil matric potential?
2. Why is a tensiometer ineffective in dry soils?

3. What is the operational range of a tensiometer?
4. Difference between soil moisture content and soil water potential?

References

Stolte, J. (Ed.). (1997). Manual for soil physical measurements. Wageningen: DLO Staring Centre.

3.5 SOIL MOISTURE CHARACTERISTIC CURVE (van Genuchten, 1980)

The determination of the Soil Moisture Characteristic Curve (SMCC) requires careful sample preparation, controlled application of suction, and sufficient equilibration time at each pressure level to obtain accurate and reproducible results. Since the SMCC represents the relationship between soil water content and soil water potential, maintaining undisturbed soil structure and preventing moisture loss during handling are essential. Each pressure step should be applied gradually, allowing the soil sample to reach hydraulic equilibrium before measurements are recorded. Proper setting and calibration of the pressure plate apparatus are critical, as errors in pressure application or equilibration can significantly affect the shape of the curve and lead to misinterpretation of soil water availability and pore-size distribution.

Aim

To determine the soil moisture characteristic curve, representing the relationship between soil water content and soil water matric potential using the pressure plate apparatus.

Principle

The soil moisture characteristic curve (SMCC) expresses the relationship between soil water content (θ) and soil water potential (matric suction). When saturated soil is subjected to increasing air pressure, water is forced out of soil pores through a porous ceramic plate. At equilibrium, the applied air pressure equals the matric potential of soil water. By measuring water content at different applied suctions, the SMCC is obtained.

Apparatus Required

- Pressure plate apparatus with air compressor
- Ceramic pressure plates (0.1–15 bar capacity)
- Undisturbed soil cores (core sampler method)
- Balance (± 0.01 g accuracy)
- Moisture cans
- Oven (105 ± 2 °C)
- Desiccator
- Distilled water

Procedure

1. Collect undisturbed soil cores using a core sampler and trim them flush with the ring edges.
2. Saturate the soil cores slowly from the bottom by placing them in a tray of distilled water for 24–48 hours to ensure complete saturation.
3. Saturate the ceramic pressure plates separately and place them inside the pressure plate chamber.
4. Place the saturated soil cores on the ceramic plates, ensuring good contact between soil and plate.
5. Close the chamber and apply the lowest air pressure (e.g., 0.1 bar).
6. Allow the system to equilibrate until no further outflow of water is observed (usually 24–72 hours).
7. Release pressure slowly, remove soil cores, and weigh them immediately to obtain moist weight.
8. Return the cores to the pressure plate and apply the next higher pressure (e.g., 0.33, 1, 3, 5, 10, and 15 bar).
9. Repeat equilibration and weighing at each pressure step.
10. After the final pressure, dry soil cores in an oven at 105 °C until constant weight to determine oven-dry weight.

Table. Observations

Applied pressure (bar)	Moist weight (g)	Oven-dry weight (g)	Gravimetric moisture (%)	Volumetric moisture (cm ³ cm ⁻³)

Calculations

Gravimetric Moisture Content

$$\theta_w = \frac{W_m - W_{od}}{W_{od}}$$

Volumetric Moisture Content

$$\theta_v = \theta_w \times \rho_b$$

where:

W_m = Moist weight of soil (g)

W_{od} = Oven-dry weight of soil (g)

ρ_b = Bulk density (Mg m⁻³)

Plotting the SMCC

Plot volumetric moisture content (θ_v) on the Y-axis against matric potential (log scale) on the X-axis to obtain the soil moisture characteristic curve.

Result

The soil moisture characteristic curve of the given soil was obtained, showing the relationship between water content and matric potential across different suction levels.

Interpretation

- Sandy soils show steep curves with rapid moisture loss at low suction.
- Clay soils show gradual curves with high water retention.
- Well-structured soils retain more plant-available water.

Precautions

- Ensure complete saturation of soil cores and ceramic plates.
- Apply pressure gradually to avoid soil disturbance.
- Avoid moisture loss during weighing.
- Ensure airtight sealing of the pressure chamber.

Applications

SMCC is used for estimating field capacity, permanent wilting point, plant-available water, and for modelling unsaturated water flow in soils.

Viva-Voce / Exam Questions

1. What is the significance of the SMCC?
2. Why is pressure plate apparatus preferred?
3. Why is suction applied stepwise?
4. How does soil texture affect SMCC?

References

van Genuchten, M.Th. (1980). Closed-form equation for hydraulic conductivity. Soil Science Society of America Journal. DOI: <https://doi.org/10.2136/sssaj1980.03615995004400050002x>

3.6 SATURATED HYDRAULIC CONDUCTIVITY (K_{sat}) (Elrick and Reynolds, 1992)

Soil hydraulic conductivity is a fundamental soil physical parameter that describes the ease with which water moves through soil pores under a hydraulic gradient. It reflects the combined influence of soil texture, structure, pore-size distribution, and pore continuity, and therefore serves as a sensitive indicator of soil physical condition. Measurement of hydraulic conductivity is essential for understanding soil water movement, drainage

behavior, and the effectiveness of irrigation and soil management practices. Under saturated conditions, all soil pores are filled with water and water flow follows Darcy's law, which relates the volume of water flowing through soil to the hydraulic gradient and cross-sectional area of flow. Saturated hydraulic conductivity (K_{sat}) is commonly measured in the laboratory using undisturbed soil cores, as this approach preserves natural soil structure and pore geometry. Accurate determination of K_{sat} requires complete saturation of the soil sample, steady-state flow conditions, and maintenance of a constant hydraulic head throughout the measurement.

Hydraulic conductivity varies widely among soils and even within the same soil profile due to differences in compaction, aggregation, biological activity, and management history. Coarse-textured and well-aggregated soils generally exhibit high hydraulic conductivity due to the presence of continuous macropores, whereas compacted or clayey soils show lower conductivity because of restricted pore connectivity. Consequently, hydraulic conductivity is highly sensitive to land use changes such as intensive tillage, heavy machinery traffic, and organic matter management.

Measurement of soil hydraulic conductivity provides critical information for designing irrigation and drainage systems, predicting waterlogging and leaching losses, and assessing soil physical quality. It is also an important input parameter for hydrological and crop growth models. Proper measurement and interpretation of hydraulic conductivity thus form an essential component of soil physics studies and sustainable soil and water management.

Aim

To determine the saturated hydraulic conductivity (K_{sat}) of soil using the constant head method.

Principle

Soil hydraulic conductivity is a measure of the ease with which water moves through soil pores under a hydraulic gradient. Under saturated conditions, all soil pores are filled with water and flow occurs according to Darcy's law, which states that the rate of water flow through a porous medium is directly proportional to the hydraulic gradient and the cross-sectional area of flow.

Mathematically, Darcy's law is expressed as:

$$Q = K A \frac{\Delta H}{L}$$

where the proportionality constant K represents the saturated hydraulic conductivity of the soil.

Apparatus Required

- Undisturbed soil core (core sampler ring)
- Constant head permeameter setup
- Water reservoir with adjustable head
- Graduated measuring cylinder or burette
- Stopwatch
- Meter scale or ruler
- Balance
- Filter paper or porous plates
- Connecting tubes

Procedure

1. Collect an undisturbed soil core using a core sampler and trim the excess soil flush with the edges of the ring.
2. Place filter paper or porous plates at both ends of the soil core to prevent soil loss.
3. Saturate the soil core slowly from the bottom upward using distilled water to avoid air entrapment.
4. Mount the saturated soil core vertically in the constant head permeameter.
5. Connect the upper end of the core to a water reservoir and adjust the water level to maintain a constant hydraulic head.
6. Allow water to flow through the soil until a steady-state flow condition is attained.
7. Collect the outflowing water for a known time interval using a graduated cylinder.
8. Measure the volume of water collected and record the time taken.

9. Measure the length of the soil core and the constant head difference across the soil column.
10. Repeat the measurements two to three times and record the average values.

Table . Observations

Observation	Symbol	Value
Length of soil core (cm)	L	
Internal radius of core (cm)	r	
Cross-sectional area (cm ²)	$A = \pi r^2$	

Observation	Symbol	Value
Hydraulic head difference (cm)	ΔH	
Volume of water collected (cm ³)	Q	
Time taken (s or min)	t	

Calculations

Saturated Hydraulic Conductivity

$$K_{sat} = \frac{Q L}{A \Delta H t}$$

Where,

K_{sat} = Saturated hydraulic conductivity (cm s⁻¹ or cm min⁻¹)

Q= Volume of water collected (cm³)

L= Length of soil column (cm)

A= Cross-sectional area of soil core (cm²)

ΔH = Hydraulic head difference (cm)

t= Time (s or min)

Result

The saturated hydraulic conductivity of the given soil was found to be _____ cm s⁻¹ (or cm min⁻¹).

Interpretation

- Higher hydraulic conductivity indicates better pore continuity and macropore development.
- Sandy and well-structured soils exhibit high K_{sat} values.
- Compacted and clayey soils show low hydraulic conductivity due to restricted pore flow.

Precautions

- Ensure complete saturation of the soil core before measurement.
- Avoid air entrapment within the soil pores.
- Maintain a truly constant hydraulic head during the experiment.
- Prevent leakage at joints and connections.
- Conduct measurements under steady-state flow conditions.

Applications

Hydraulic conductivity measurements are essential for evaluating soil drainage capacity, designing irrigation and drainage systems, predicting leaching losses, and assessing soil physical quality under different land-use systems.

Viva-Voce / Exam Questions

1. State Darcy's law.
2. Why is hydraulic conductivity higher under saturated conditions?
3. Difference between saturated and unsaturated hydraulic conductivity.
4. Why is K_{sat} highly variable spatially?

Reference

Elrick, D. E., & Reynolds, W. D. (1992). Methods for analyzing constant-head well permeameter data. *Soil Science Society of America Journal*, 56(1), 320–323.
<https://doi.org/10.2136/sssaj1992.03615995005600010052x>

3.7 INFILTRATION RATE (Horton, 1940)

Measurement of infiltration rate requires careful site selection, proper installation of the infiltrometer, and controlled water application to obtain reliable results. Since infiltration is strongly influenced by soil surface condition, initial soil moisture, and structural stability, the soil surface should remain undisturbed during installation and measurement. Adequate time must be allowed for the infiltration rate to approach a steady state, and lateral flow should be minimized to ensure that the observed water movement represents true vertical infiltration. Accurate timing and consistent maintenance of water head are essential, as small errors in observation can lead to significant variation in calculated infiltration rates.

Aim

To determine the infiltration rate of soil using a double ring infiltrometer and to assess the soil's capacity to absorb water under field conditions

Principle

Infiltration rate is the rate at which water enters the soil surface under the influence of gravity and capillary forces. When water is applied to the soil surface, it moves downward through soil pores, initially at a high rate due to dry soil conditions and strong capillary forces. As the soil becomes wetter, the infiltration rate gradually decreases and eventually approaches a constant value, known as the basic or steady-state infiltration rate. In the double ring infiltrometer method, the outer ring restricts lateral movement of water, ensuring that the measured infiltration in the inner ring primarily represents vertical water flow into the soil.

Apparatus Required

- Double ring infiltrometer set
 - Inner ring: 25–30 cm diameter
 - Outer ring: 45–60 cm diameter
- Driving plate and hammer
- Measuring scale or hook gauge
- Stopwatch

- Water supply (bucket or tank)
- Spirit level
- Plastic sheet (optional, to reduce soil disturbance)

Procedure

1. Select a representative and level site, free from cracks, stones, vegetation, and animal burrows.
2. Place the inner and outer rings concentrically on the soil surface.
3. Drive both rings vertically into the soil to a depth of 10–15 cm using a hammer and driving plate, ensuring minimal disturbance and maintaining vertical alignment.
4. Place a plastic sheet inside both rings (optional) and gently pour water to avoid soil surface sealing. Remove the sheet carefully after filling.
5. Fill both rings with water up to a fixed depth (usually 5–10 cm).
6. Start the stopwatch immediately after filling.
7. Measure the drop in water level in the inner ring at regular time intervals (e.g., 1, 3, 5, 10, 15, 30 minutes).
8. Maintain the same water level in the outer ring throughout the experiment to ensure lateral flow control.
9. Continue observations until the infiltration rate becomes nearly constant (steady- state infiltration).
10. Record time and corresponding drop in water level in the inner ring.

Observations

Time (min)	Water level drop (cm)	Cumulative infiltration rate (cm)

Calculations

(A) Infiltration Rate

$$\text{Infiltration Rate (IR)} = \frac{\Delta h}{\Delta t}$$

where:

- Δh = Change in water depth in the inner ring (cm)
- Δt = Time interval (hours)

$$\text{IR} = \frac{\text{cm}}{\text{hr}}$$

(B) Cumulative Infiltration

$$\text{Cumulative Infiltration} = \sum \Delta h$$

(C) Steady-State Infiltration Rate

The constant infiltration rate attained after a sufficiently long time represents the basic infiltration rate of the soil.

Interpretation

- High infiltration rate indicates good soil structure and macroporosity.
- infiltration rate suggests compaction, surface crusting, or poor aggregation.
- Sandy soils generally show high infiltration rates, while clayey and compacted soils show low rates.

Applications

- Infiltration rate measurements are used for selecting appropriate irrigation methods by matching soil intake capacity with the rate of water application.
- They are also important for predicting surface runoff, as soils with low infiltration rates generate higher runoff during rainfall or irrigation.
- In addition, infiltration data support soil conservation planning by helping identify erosion-prone soils and design suitable land and water management practices.

Precautions

- Rings must be inserted vertically without tilting.

- Avoid disturbing the soil surface during installation.
- Maintain constant water head in the outer ring.
- Conduct the test under uniform initial soil moisture conditions.

Reference

Horton, R. E. (1940). An approach toward a physical interpretation of infiltration-capacity. Soil Science Society of America Journal, 5, 399–417.

<https://doi.org/10.2136/sssaj1940.036159950005000C0075x>

3.8 SOIL WATER DIFFUSIVITY (Bruce and Klute, 1956)

Measurement of soil water diffusivity requires uniform soil packing, precise control of initial moisture conditions, and careful monitoring of wetting front movement to ensure accurate estimation of water redistribution under unsaturated conditions. Since soil water diffusivity is highly dependent on moisture content, the experiment must be conducted under well- defined boundary conditions and with minimal disturbance to the soil column. Rapid sampling and moisture determination are essential to avoid evaporation losses, and preferential flow along column walls must be prevented. Proper setting and execution of the experiment are critical, as small errors in moisture measurement or timing can lead to significant deviations in calculated diffusivity values and misinterpretation of soil water movement behaviour.

Aim

To determine the soil water diffusivity (D) under unsaturated conditions using a soil column method.

Principle

Soil water diffusivity describes the rate at which soil water moves in response to a gradient in soil water content under unsaturated conditions. It combines the effects of soil water retention and unsaturated hydraulic conductivity and governs the redistribution of water within the soil profile after rainfall or irrigation. The diffusivity is determined by monitoring the advance of a wetting front in a soil column and relating moisture content changes to time and distance.

Mathematically, soil water diffusivity is expressed as:

$$D(\theta) = \frac{K(\theta)}{C(\theta)}$$

where $K(\theta)$ is the unsaturated hydraulic conductivity and $C(\theta)$ is the soil water capacity

Apparatus Required

- Soil column (transparent acrylic or glass)
- End caps with porous plates or filter paper
- Stand to hold the soil column vertically
- Balance (± 0.01 g accuracy)
- Moisture cans
- Oven (105 ± 2 °C)
- Distilled water
- Stopwatch
- Ruler or measuring scale
- Soil auger and sieve (2 mm)

Procedure

1. Collect surface soil, air-dry, and pass through a 2 mm sieve.
2. Pack the soil uniformly into the soil column to a known bulk density.
3. Close the bottom of the column with a porous plate or filter paper to prevent soil loss.
4. Bring the soil column to a uniform initial moisture content (preferably air-dry condition).
5. Apply water at the top of the column to initiate infiltration, maintaining a constant water supply.
6. Allow the wetting front to advance through the soil column.
7. At predetermined time intervals, stop the experiment and section the column at known distances from the soil surface.
8. Collect soil samples from each section in moisture cans.

9. Determine gravimetric moisture content of each section by oven drying at 105 °C.

10. Calculate volumetric moisture content using bulk density.

Observations

Distance from surface (cm)	Time (min)	Gravimetric moisture (%)	Volumetric moisture (cm ³ cm ⁻³)

Calculations

1. Volumetric Water Content

$$\theta_v = \theta_w \times \rho_b$$

2. Soil Water Diffusivity

Using the Boltzmann transformation:

$$D(\theta) = \frac{1}{2t} \left(\frac{dx}{d\theta} \right)^2$$

where:

$D(\theta)$ = Soil water diffusivity (cm² min⁻¹)

x = Distance from soil surface (cm)

t = Time (min)

θ = Volumetric moisture content

Plot θ versus x/\sqrt{t} and determine diffusivity from the slope.

Result

Soil water diffusivity of the given soil was found to be _____ $\text{cm}^2 \text{min}^{-1}$ at moisture content ____.

Interpretation

- Higher diffusivity indicates rapid redistribution of soil water.
- Sandy soils exhibit higher diffusivity at low moisture content.
- Clay soils show higher diffusivity near saturation.

Precautions

- Maintain uniform bulk density while packing soil.
- Avoid preferential flow along column walls.
- Ensure accurate moisture measurement.
- Perform sectioning quickly to avoid evaporation losses.

Applications

Soil water diffusivity is essential for understanding post-irrigation water redistribution, designing irrigation schedules, modelling unsaturated water flow, and evaluating soil physical quality in dryland agriculture.

Viva-Voce / Exam Questions

1. What is soil water diffusivity?
2. How is diffusivity related to hydraulic conductivity?
3. Why is diffusivity moisture-dependent?
4. Difference between diffusivity and permeability?

References

Bruce, R. R., & Klute, A. (1956). The measurement of soil water diffusivity. *Soil Science Society of America Journal*, 20(4), 458–462.
<https://doi.org/10.2136/sssaj1956.03615995002000040008x>

CHAPTER 4

SOLUTE TRANSPORT THROUGH SOIL (van Genuchten and Wierenga, 1976)

Measurement of solute transport through soil requires uniform soil packing, controlled water flow, and accurate monitoring of solute movement to obtain meaningful and reproducible results. Since solute transport is influenced by both soil hydraulic properties and soil–solute interactions, it is essential to maintain steady flow conditions and apply the solute solution at a known and constant concentration. Care must be taken to avoid preferential flow, air entrapment, and disturbance of the soil column, as these can significantly alter solute breakthrough behavior. Precise collection and analysis of effluent samples at regular time intervals are critical, as errors in sampling or concentration measurement can lead to incorrect estimation of solute diffusion and dispersion parameters.

Aim

To study the transport of a solute through soil and to determine solute transport parameters such as dispersion coefficient and retardation behavior using a soil column method.

Principle

Solute transport in soil occurs mainly through the liquid phase and is governed by physical processes such as advection, diffusion, and dispersion, along with soil–solute interactions like adsorption. When a solute solution is applied to a soil column under steady water flow, the movement of solute through the soil profile can be monitored by analyzing solute concentration in the effluent over time.

The variation of solute concentration in the effluent with time is represented by a breakthrough curve, which provides information on solute mobility, spreading, and retention within the soil.

Apparatus Required

1. Soil column (PVC, acrylic, or glass) with known length and diameter
2. End caps fitted with filter paper or porous plates

3. Constant head water supply or peristaltic pump
4. Collection bottles or test tubes
5. Stopwatch
6. Measuring cylinder or burette
7. Balance (± 0.01 g accuracy)
8. Conductivity meter or spectrophotometer (depending on solute)
9. Distilled water
10. Selected solute (e.g., KCl, NaCl, or dye solution)
11. Soil auger and 2 mm sieve

Procedure

1. Collect soil, air-dry, and pass through a 2 mm sieve.
2. Pack the soil uniformly into the column to a predetermined bulk density, avoiding layering and air entrapment.
3. Place filter paper or a porous plate at the bottom of the column to prevent soil loss.
4. Saturate the soil column slowly from the bottom with distilled water to remove entrapped air.
5. Establish a steady downward flow of distilled water through the column under constant head conditions.
6. Once steady flow is achieved, replace distilled water with a solute solution of known concentration at the top of the column.
7. Collect effluent samples at fixed time intervals using collection bottles.
8. Measure solute concentration in each effluent sample using a conductivity meter or spectrophotometer.
9. Continue sampling until the effluent concentration approaches the influent concentration.
10. Record time, volume of effluent, and corresponding solute concentration.

Observations

Time (min)	Effluent volume (ml)	Solute concentration (C)	C/C ₀

where C₀ is the concentration of the applied solute solution.

Calculations

(A) Pore Water Velocity

$$v = \frac{Q}{A \times \theta}$$

Where,

v = pore water velocity (cm min⁻¹)

Q = flow rate (cm³ min⁻¹)

A = cross-sectional area of column (cm²)

θ = volumetric water content (cm³ cm⁻³)

(B) Dispersion Coefficient (D)

From the breakthrough curve (C/C₀ vs time), the dispersion coefficient is estimated using standard transport equations or slope analysis:

$$D = \alpha \times v$$

Where,

D = dispersion coefficient (cm² min⁻¹)

α = dispersivity (cm)

v = pore water velocity

(C) Retardation Factor (if applicable)

$$R = \frac{t_{0.5, \text{soil}}}{t_{0.5, \text{tracer}}}$$

where $t_{0.5}$ is the time at which $C/C_0 = 0.5$.

4.6 Graphical Representation

- Plot C/C_0 versus time to obtain the breakthrough curve.
- The shape and spread of the curve indicate solute mobility and dispersion.

Result

1. The dispersion coefficient of the soil for the applied solute was found to be _____ $\text{cm}^2 \text{min}^{-1}$.
2. The breakthrough curve indicated _____ (high/low) solute mobility.

Interpretation

1. Early breakthrough indicates high permeability or preferential flow.
2. Delayed breakthrough suggests adsorption or low pore connectivity.
3. Well-structured soils show smoother breakthrough curves compared to compacted soils.

Precautions

1. Maintain uniform soil packing and bulk density.
2. Ensure steady-state flow before solute application.
3. Avoid air entrapment during saturation.
4. Collect effluent samples at consistent time intervals.

Applications

Solute transport studies are essential for predicting nutrient leaching, assessing groundwater contamination risk, managing fertilizer and pesticide applications, and understanding pollutant movement in soils.

Viva-Voce / Exam Questions

1. What is a breakthrough curve?
2. Difference between diffusion and dispersion?
3. Why is solute transport faster in sandy soils?
4. How does adsorption affect solute movement?

References

1. van Genuchten, M.Th., & Wierenga, P.J. (1976). Solute dispersion coefficients. DOI: <https://doi.org/10.2136/sssaj1976.03615995004000040024x>

CHAPTER 5

SOIL PHYSICAL QUALITY PARAMETERS

Soil physical quality refers to the capacity of soil to perform essential physical functions required for plant growth, environmental regulation, and sustainable land use. These functions include the ability of soil to provide mechanical support for roots, store and transmit water and air, resist physical degradation, and maintain structural stability under varying climatic and management conditions. Unlike individual soil physical properties, soil physical quality represents an integrated assessment of soil behavior that reflects the combined influence of texture, structure, porosity, and compaction.

Soil physical quality parameters are increasingly used as diagnostic indicators to evaluate soil degradation, monitor the impacts of land use change, and assess the effectiveness of soil and water management practices. These parameters translate complex physical measurements into interpretable metrics that are directly linked to soil function and crop performance.

5.1 Soil Organic Carbon as a Physical Quality Indicator

Soil organic carbon (SOC) plays a central role in determining soil physical quality by influencing aggregation, porosity, and water retention. Organic carbon acts as a binding agent that stabilizes soil aggregates and promotes the formation of stable macro- and micropores. Soils with higher organic carbon content generally exhibit lower bulk density, higher infiltration rates, and greater resistance to compaction.

From a soil physical perspective, SOC improves soil resilience by enhancing structural stability and increasing the soil's capacity to buffer against wetting–drying cycles. Declining SOC is often associated with structural degradation, surface crusting, and reduced hydraulic conductivity, making it a key indicator of soil physical health.

5.2 Least Limiting Water Range (LLWR)

The Least Limiting Water Range (LLWR) is an integrative soil physical quality parameter that defines the range of soil water content within which limitations due to water availability, aeration, and mechanical resistance are minimal. LLWR is bounded by upper and lower limits determined by field capacity, air-filled porosity, permanent wilting point, and soil penetration resistance.

A wider LLWR indicates favourable soil physical conditions for root growth and biological activity, whereas a narrow or zero LLWR reflects severe physical constraints, often caused by compaction or structural degradation. LLWR is particularly useful for comparing soil physical quality across land uses and management systems.

5.3 Physical Rating of Soils for Crop Production

Physical rating systems evaluate soil suitability for crop growth based on key physical attributes such as bulk density, texture, structure, infiltration, and available water capacity. These ratings classify soils into categories ranging from physically optimal to severely constrained.

Such ratings provide a practical framework for diagnosing soil physical limitations, guiding land management decisions, and identifying soils requiring physical amelioration through practices such as organic amendments, reduced tillage, or deep loosening.

Interpretation of Soil Physical Quality Indicators

Soil physical quality indicators must be interpreted in relation to soil type, climate, and cropping system. Threshold values for parameters such as bulk density, porosity, or LLWR vary with texture and mineralogy. Therefore, site-specific evaluation is essential for meaningful assessment.

Applications of Soil Physical Quality Assessment

Assessment of soil physical quality supports sustainable land management by enabling early detection of degradation, evaluation of management impacts, and formulation of corrective measures. These indicators are widely applied in soil conservation planning, irrigation management, climate-resilient agriculture, and long-term soil monitoring programs.

Viva-Voce / Concept Questions

1. Why is soil physical quality considered an integrative concept?
2. How does organic carbon influence soil physical quality?
3. What makes LLWR superior to individual physical parameters?
4. Why are threshold values soil-specific?