2
Basic Definitions and Concepts: Soil Components and Phases

Most soils consist of four components and three phases (Fig. 2.1). The four components include inorganic solids, organic solids, water, and air. Inorganic components are primary and secondary minerals derived from the parent material. Organic components are derived from plants and animals. The liquid component consists of a dilute aqueous solution of inorganic and organic compounds. The gaseous component includes soil air comprising a mixture of some major (e.g., nitrogen, oxygen) and trace gases (e.g., carbon dioxide, methane, nitrous oxide). Under optimal conditions for growth of upland plants, the solid components (inorganic and organic) constitute about 50% of the total volume, while liquid and gases comprise 25% each (Fig. 2.2a). Rice and other aquatic plants are exceptions to this generalization. The organic component for most mineral soils is about 5% or less. Immediately after rain or irrigation, the entire pore space or the voids in between the solids are completely filled with water, and the soil is saturated (Fig. 2.2b). When completely dry, the water in the pores is replaced by air or gases (Fig. 2.2c). General properties of components and phases are listed in Table 2.1. Under optimal conditions for some engineering functions, such as foundation for buildings and roads or runways, the pore space is deliberately minimized by compaction or compression. For such functions, the solid components may compose 80–90% of the total volume. There must be little if any liquid component for the foundation to be stable. Some industrial functions (e.g., dehalogenation) may require anaerobic conditions, however.

Anaerobiosis may lead to transformation of organic matter by the attendant methanogenesis and emissions of methane (CH_4) to the atmo-sphere. In contrast, oxidation and mineralization of organic matter may cause release of carbon dioxide (CO_2) to the atmosphere. Filtration of pollutants and sequestration of carbon (C) in soil as soil organic carbon (SOC), two important environmental functions, also depend on an optimal balance between four components and three phases. The dynamic equilibrium between components and phases can be altered by natural or anthropogenic perturbations.

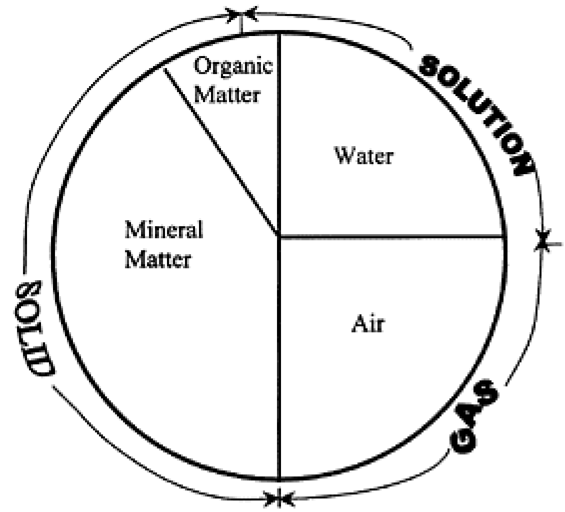

FIGURE 2.1 Soil is made up of four components and three phases.

2.1 DEFINITIONS

Soil physics deal with the study of soil physical properties (e.g., texture, structure, water retention, etc.) and processes (e.g., aeration, diffusion, etc.). It also consists of the study of soil components and phases, their interaction with one another and the environment, and their temporal and spatial variations in relation to natural and anthropogenic or management factors (Fig. 2.3). Soil physics involves the application of principles of physics to understand interrelationship of mass and energy status of components and phases as dynamic entities. All four components are always changing in their relative mass, volume, spatial and energy status due both to natural and management factors.

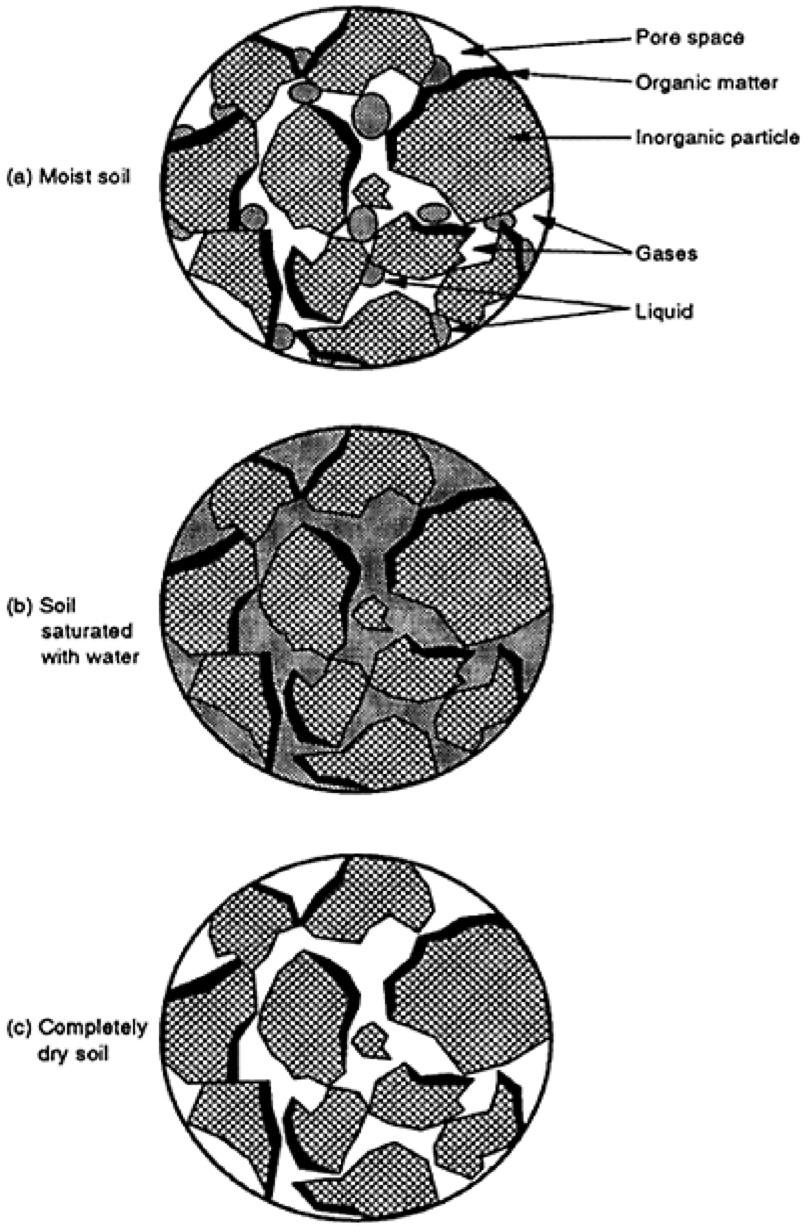

FIGURE 2.2 Interaction among four components and three phases for (a) moist, (b) water-saturated, and (c) completely dry soil.

Table 2.1 Properties and Phases and Components

Phases	Components	Composition	Properties
Solid	Inorganic	Products of weathering; quartz, feldspar, magnetite, garnet, hornblonde, silicates, secondary minerals	Skeleton, matrix ρ_s=2.0–2.8 Mg/m^3
	Organic	Remains of plants and animals; living organisms, usually <5%	Large surface area, very active, affects CO_2 in the atmosphere ρ_s=1.2− 1.5 Mg/m^3
Liquid	Soil solution	Aqueous solution of ions (e.g., Na, K, Ca, Mg, Cl, NO_3, PO_4, SO_4)	Heterogeneous, dynamic, discontinuous ρw=1.0 Mg/m^3
Gas	Soil air	N_2, O_2, CO_2, CH_4, C_2H_6, H_2S, N_2O, NO	ρ_a=1–1.5 kg/m^3 variable, dynamic

ρ_s=particle density, l_w=density of H2O, l_a=density of air.

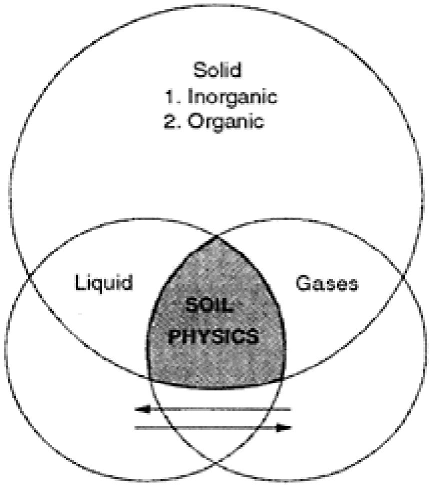

FIGURE 2.3 Soil physics is the study of properties and interaction among four components and three phases. Under optimal conditions for growth of upland plants, the solid phase composes about 50% of the total volume, and liquid and gaseous phases each compose 25% by volume. The volume of liquids increase at the expense of gases and vice versa.

Consider a unit quantity of soil with total mass *(M_t)* consisting of different components namely solids (M_s, which includes mass of inorganic component M_{in} and organic components M_o), liquids *(M_l)* and gases (M_g, which is negligible and can be taken as zero for all practical purposes) (Fig. 2.4). Similarly, the total volume *(V_t)* comprises volume of its different components namely solids *(V_s)*, which includes volume of inorganic components *(V_{in})* and organic components *(V_o)*, liquids *(V_l)* and gases *(V_g)*. Different soil physical properties are defined in the following sections.

2.1.1 Soil Density *(ρ)*

Density is the ratio of mass and volume. It is commonly expressed in the units of g/cm^3 and Mg/m^3 (lbs/ft^3). Density is defined in four ways as follows:

1. *Particle density (ρ_s):* It is also called the true density, and is the ratio of mass of solid *(M_s)* divided by the volume of solid *(V_s)* [Eq. (2.1)].

$$\rho_s = M_s/V_s = (M_{in}+M_o)/(V_{in}+V_o) \tag{2.1}$$

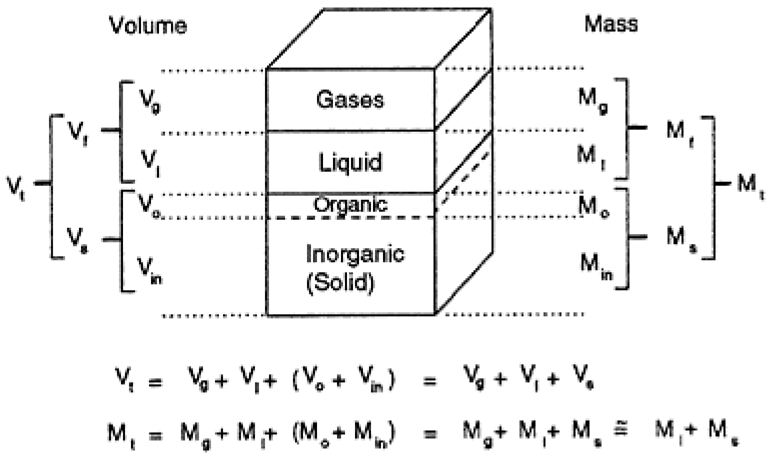

FIGURE 2.4 A schematic showing the mass *(M)* and volume *(V)* relationship of four soil components. Subscripts *f, g, l, o, in, s,* and *t* refer to fluids, gases, liquid, organic, inorganic, solid, and total, respectively.

Particle density of inorganic soils ranges from 2.6 to 2.8 g/cm^3 or Mg/m^3, and those of minerals commonly found in soils is shown in Table 2.2. Note that density of organic matter is about half of that of the inorganic mineral. In comparison, the density of water is about 1.0 Mg/m^3 and that of the air about 1.0 kg/m^3.

2. *Bulk density* (ρ_b): It is also called the apparent density, and is the ratio of mass of solid (M_s) to the total volume (V_t). Soil bulk density can be defined as wet (ρ'_b) that includes the mass of water [Eq. (2.2)], and dry (ρ_b) which is without water [Eq. (2.3)]. Its units are also that of mass/volume as g/cm^3 or Mg/m^3.

$$\rho'_b = \frac{M_s + M_w}{V_t} = \frac{(M_{in} + M_o + M_w)}{(V_s + V_w + V_g)} \tag{2.2}$$

$$\rho_b = \frac{M_s}{V_t} = \frac{M_{in} + M_o}{V_s + V_g} \tag{2.3}$$

In a dry soil, V_w is zero. Wet soil bulk density is an ever changing entity because of soil evaporation at all times under natural conditions. Therefore, soil bulk density is preferably reported as a dry soil bulk density. A dense soil has more solids per unit volume (Fig. 2.4a) than a porous soil (Fig. 2.5b). Methods of measurement of ρ_b are described by Campbell et al. (2000) and Culley (1993).

Table 2.2 Particle Density of Some Common Soil Minerals, Organic Matter, Water and Air

Mineral	Particle density (Mg/m^3)	Other constituents	Particle density (Mg/m^3)
Biotite	2.7–3.3	Soil organic matter	1.0–1.4
Brucite	2.38–3.40	Water	1.0
Calcite	2.72–2.94	Air	10×10^{-3}
Chlorite	2.60–3.3		
Diamond	3.50–3.53		
Dolomite	2.86		
Gibbsite	2.38–2.42		
Geothite	3.3–4.3		
Gypsum	2.3–2.47		
Hematite	5.26		
Hornblende	3.02–3.45		
Illite	2.60–2.90		
Kaolinite	2.61–2.68		
Magnetite	5.175		
Montmorillonite	2.0–3.0		
Muscovite	2.77–2.88		
Orthoclase	2.55–2.63		
Pyrite	5.018		

Quartz	2.65
Serpentine	2.55
Talc	2.58–2.83
Tourmaline	3.03–3.25
Vermiculite	2.3

Source: Adapted from Handbook of Chemistry and Physics (1988).

3. *Relative density or specific gravity (G_s):* Specific gravity is the ratio of particle density of a soil to that of the water. Being a ratio, it is a dimensionless entity, and is expressed as shown in Eq. (2.4).

$$G_s = \rho_s / \rho_w \tag{2.4}$$

4. *Dry specific volume (V_b):* It is defined as the reciprocal of the dry bulk density [Eq. (2.5)] and has units of volume divided by mass or cm^3/g or m^3/Mg.

$$V_b = \frac{1}{\rho_b} = \rho_b^{-1} = \frac{V_t}{M_s} = \frac{(V_s + V_f)}{(M_s + M_e)} \tag{2.5}$$

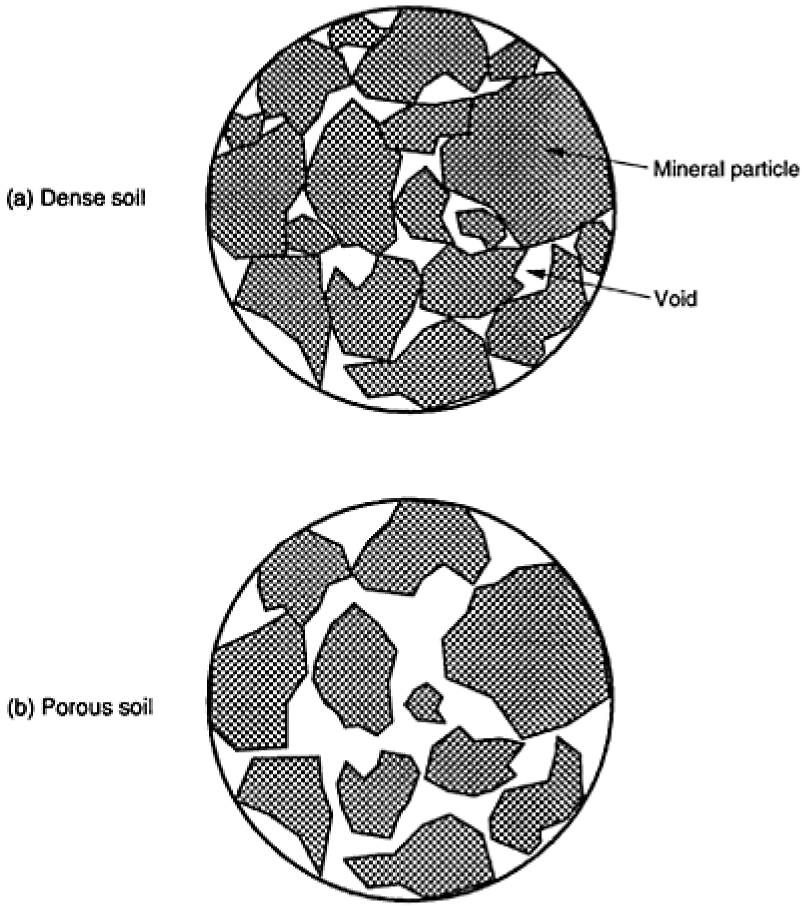

FIGURE 2.5 Dense soils are suitable for engineering functions and porous soils for agricultural land use.

2.1.2 Soil Porosity *(f)*

Porosity refers to the relative volume of voids or pores, and is therefore expressed as a fraction or percent of the total volume or of the volume of solids. Soil porosity can be expressed in the following four ways:

1. *Total porosity* (f_t): It is the ratio of volume of fluids or water plus air (V_f) to total volume (V_t), as shown in Eq. (2.6).

$$f_t = \frac{V_f}{V_t} = \frac{V_g + V_l}{V_s + V_l + V_g} \tag{2.6}$$

2. *Air-filled porosity* (f_a): It refers to the relative proportion of air-filled pores [Eq. (2.7)].

$$f_a = \frac{V_g}{V_t} \qquad (2.7)$$

In relation to plant growth, the critical limit of air-filled porosity is 0.10 or 10%, below which plant growth is adversely affected due to lack of sufficient quantity of air or anaerobiosis. Air porosity is also equal to total porosity minus the volumetric moisture content (Θ) as computed in Eq. (2.11).

3. *Void ratio (e):* In relation to engineering functions, where porosity should be usually as low as possible, the relative proportion of voids to that of solids is expressed as void ratio [Eq. (2.8)]. Being a ratio, it is also a dimensionless quantity.

$$e = \frac{V_f}{V_s} = \frac{(V_g + V_l)}{(V_{in} + V_o)} \qquad (2.8)$$

4. *Air ratio* (α): It is defined as the ratio of volume of air to that of the solids [Eq. (2.9)] and has relevance to plant growth and engineering applications.

$$\alpha = \frac{V_g}{V_s} = \frac{V_g}{(V_{in} + V_o)} \qquad (2.9)$$

2.1.3 Soil Moisture Content

Soil moisture is the term used to denote water contained in the soil. Soil water is usually not free water, and is, therefore, called soil moisture. Soil moisture content can be expressed in the following four ways:

1. *Gravimetric soil moisture content (w):* It is the ratio of mass of water *(M_w)* to that of solids *(M_s)*, and is expressed either as fraction or percent [Eq. (2.10)].

$$w = \frac{M_w}{M_s} = \frac{M_w}{(M_{in} + M_o)} \qquad (2.10)$$

2. *Volumetric soil moisture content* (Θ): In relation to agricultural and engineering functions, it is more relevant to express soil moisture content on volumetric than on gravimetric basis. Similar to *w*, Θ is also expressed as a ratio or percent [Eq. (2.11)].

$$\theta = \frac{V_w}{V_t} = \frac{V_l}{(V_s + V_f)} \qquad (2.11)$$

3. *Liquid ratio (θρ):* Just as in case of void ratio, the liquid ratio has also numerous engineering applications, and is expressed as a ratio [Eq. (2.12)].

$$\theta_\rho = \frac{V_w}{V_s} = \frac{V_w}{(V_{in} + V_o)} \qquad (2.12)$$

The liquid ratio is also a useful property for soils with high swell-shrink properties.

4. *Degree of saturation (s):* It refers to the relative volume of pore space containing water or liquid in relation to the total porosity [Eq. (2.13)], and is also expressed as a fraction or percentage.

$$s = \frac{V_w}{V_f} = \frac{V_w}{(V_l + V_s)} \qquad 2.13$$

2.1.4 Soil Physical Quality

Thirteen soil physical properties defined above are extremely important in defining soil physical quality in relation to specific soil functions (see Chapter 1; Arshad et al., 1996; Lowery et al., 1996). The objectives of soil management are to optimize these properties for specific soil functions. One or an appropriate combination of these properties is used as an index of soil physical quality. Indicators of soil quality, however, differ among soils and specific functions. The normal range of these indicators is shown in Table 2.3.

General physical properties of three phases and four components are shown in Table 2.4. Solids form the skeleton of the soil or soil matrix in which fluids constitute the plasma. Particle density of the inorganic components is almost twice that of the organic components. The liquid phase is a dilute aqueous solution of numerous salts including nitrates, chlorides, sulphates, carbonates, and phosphate of K, Ca, Mg, Na, and other cations. Soil air or the gaseous phase contains more CO_2 and less O_2 than atmospheric air (see Chapter 18).

TABLE 2.3 Normal Range of Soil Physical Properties in Relation to Plant Growth

Soil physical property	Range	Units
Particle density *(ρ_s)*	2.6–2.8	g/cm^3, Mg/m^3
Dry bulk density *(ρ_b)*	0.7–1.8	g/cm^3, Mg/m^3
Porosity *(f_t)*	0.3–0.7	Fraction, m^3/m^3
Air porosity *(f_a)*	$0-f_t$	Fraction, m^3/m^3
Void ratio *(e)*	0.4–2.2	Fraction
Gravimetric soil moisture content *(w)*	0–0.3	Fraction, kg/kg
Volumetric soil moisture content (Θ)	0–0.7	Fraction, m^3/m^3
Degree of saturation *(s)*	0–1	Fraction
Dry specific volume *(V_b)*	0.5–1	cm^3/g, m^3/Mg
Air ratio *(α)*	0–1	Dimensionless
Liquid ratio *(θ_p)*	0–1	Dimensionless
Wet bulk density *(ρ'_b)*	1–2	g/cm^3, Mg/m^3

2.2 INTERRELATIONSHIP AMONG SOIL PROPERTIES

Several of these properties are interrelated and one can be computed from another. Specific examples of these interrelationships are shown below:

$$\theta = w\rho_b/\rho_w \quad (2.14)$$

$$\theta = \frac{\rho'_b - \rho_b}{\rho_w} \quad (2.15)$$

$$ft = (1 - \rho_b/\rho_s) \quad (2.16)$$

$$e = (\rho_s/\rho_b) - 1 \quad (2.17)$$

$$\theta_{\rho=}\Theta(1+e) \quad (2.18)$$

$$f_t = f_a + \theta \quad (2.19)$$

$$\rho_b = \rho_s(1 - f_t) \quad (2.20)$$

$$w = \frac{\rho'_b - \rho_b}{\rho_b} \quad (2.21)$$

TABLE 2.4 General Properties of Phases and Components

Phase	Component	Composition	General properties
Solid	Inorganic	Products of weathering of rocks and minerals. Mostly comprise primary and secondary minerals e.g. quartz, feldspar, magnetite, garnet, hornblende, silicates, and secondary minerals. Usually compose 95% of the dry soil mass.	Skeleton, matrix, ρ_s of 2.6−2.8 g/cm^3. Surface area and charge density depend on size distribution,
	Organic	Remains of plants and animals at various stages of decay and decomposition. Usually comprise <5% of the dry soil mass.	This fraction is highly reactive and dynamic. It has large surface area and high charge density. ρ_s ranges from 1.2 to 1.5 g/cm3.
Liquid	Soil solution	Aqueous and dilute solution of numerous ions. Predominant ions depend on the parent material and land use and may comprise Na, K, Ca, Mg, Cl, NO_3, PO_4, and SO_4.	This is a very heterogenous solution, and is highly variable in time and space. This phase is discontinuous and increases or decreases depending on the degree of wetness and density of soil.

Gas	Soil air	Composition of soil air differs than that of the atmosphere. Soil air comprises a mixture of numerous gases including N_2, O_2, CO_2, CH_4, C_2H_6, H_2S, N_2O, NO, and others.	Composition of soil air is extremely heterogenous, very dynamic, and highly variable over time and space. This is also a discontinuous phase and varies inversely with volume of soil solution. Approximate density of soil air is 1–1.5 kg/m^3.

2.3 ASSESSMENT OF SOIL PARTICLE DENSITY

Methods of assessment of ρ_b, f_t, f_a, w, and Θ are discussed under appropriate sections. There are two common procedures of determining soil particle density. One is based on calculations from the particle density of its constituents [Eq. (2.22)].

$$\frac{1}{\rho_s}=\frac{x_1}{\rho_{s1}}+\frac{x_2}{\rho_{s2}}+\frac{x_3}{\rho_{s3}} \tag{2.22}$$

where x_1, x_2, and x_3 are weight fractions of the constituents, and ρ_{s1}, ρ_{s2}, and ρ_{s3} are the corresponding particle densities of those fractions. The second method of determining the particle density involves the laboratory procedure based on the Archimedes' principle. This procedure involves measurement of the volume displacement of dry soil by a liquid of known density using a pycnometer (Blake and Hartge, 1986). In addition, eletronic pycnometers are also available.

Example 2.1

A soil is sampled by a core measuring 7.6 cm in diameter and 7.6 cm deep. The core weighs 300 g. The total core plus wet soil weight is 1000 g. On oven drying at 105° C the core plus dry soil weighed 860 g. Calculate wet and dry bulk densities and gravimetric moisture contents.

Solution

Total volume of core = $\pi r^2 h$ = 3.14 (3.8 cm^2)·7.6 cm=345 cm^3
Core weight = 300 g
Weight of wet soil = 1000 g−300 g=700 g
Weight of dry soil = 860 g−300 g=560 g
Wet bulk density (M_t/V_t)=700 g/345 cm^3=2.03 g/cm^3
Dry bulk density (M_s/V_t)=560 g/345 cm^3=1.62 g/cm^3
Gravimetric moisture content $(w)=M_w/M_s$=(1000 g−860 g)/ 560 g
= 140 g/560 g
=0.25 or 25%

Example 2.2

One liter of dry soil sampled from a farm requires 300 g of water to completely saturate it. Calculate: (a) its porosity and (b) volume of water required to saturate the plow layer (20 cm) of 1 hectare of the farmland.

Solution
(a) Porosity (ft)=V_w/V_t=300 cm^3/1000 cm^3=0.3 m^3/m^3
(b) Depth of water *(Q)*=$f_t \cdot d$, where *d* is depth =0.3×20 cm=6 cm
Total volume of water for one ha=6×10^5 L

Example 2.3

A soil in the greenhouse container has a wet bulk density of 1.7 Mg/m^3 and dry bulk density of 1.4 Mg/m^3. Calculate gravimetric and volumetric soil moisture contents, and air-filled porosity.

Solution

$$w = \frac{\rho'_b - \rho_b}{\rho_b} = \frac{1.7 - 1.4}{1.4} = 0.214\,\text{kg/kg}$$

$$\Theta = \frac{\rho'_b - \rho_b}{\rho_w} = \frac{1.7 - 1.4}{1.0} = 0.3\,\text{m}^3/\text{m}^3$$

$$f_a = 1 - (V_s + V_w) = 1 - \left(\frac{1.4}{2.65} + 0.3\right) = 0.172\,\text{m}^3/\text{m}^3$$

An alternative solution is to assume the volume of the container.
Let the pot volume=1000 cm3
Particle density=2.65 g/cm^3
Wet soil weight=1000 cm^3×1.7 g/cm^3=1700 g
Similarly, dry soil weight=1400 g
Mass of water *(M_w)*=1700 g−1400 g=300 g
Volume of water *(V_w)*=300 cm^3
Gravimetric moisture content *(W)*=300 g/1400 g=0.214 kg/kg or 21.4%
Volumetric moisture content (Θ)=300 cm^3/1000 cm^3=0.30 m^3/m^3 or 30%
Volume of solids=mass/density=1400 g/2.63 g/cm^3=528.3 cm^3
Air porosity *(f_a)*=(1000 cm^3−528.3 cm^3−300 cm^3)/1000 cm^3
=171.7 cm^3/1000 cm^3=0.172 m^3/m^3 or 17.2%

Example 2.4

One liter of soil has a wet weight of 1500 g, dry weight of 1200 g, and volume of soil solids of 450 cm^3. Compute all 13 soil physical properties.

Solution

1. $\rho_s = M_s/V_s$=1200 g/450 cm^3=2.67 g/cm^3
2. $\rho_b = M_s/V_t$=1200 g/1000 cm^3=1.20 g/cm^3
3. $\rho_b = (M_s + M_w)/V_t$=1500 g/1000 cm^3=1.5 g/cm^3
4. $G_s = \rho_s/\rho_w$=2.67
5. $V_b = 1/\rho_b$=0.83 cm^3/g
6. $f_t = (1-\rho_b/\rho_s)$=(1−1.2/2.67)=0.55 or 55%
7. $f_a = 1-(V_s + V_w)$=1−(450/1000+ 300/1000)=1−0.75=0.25 or 25%
8. $e = Vf/V_s$=550cm^3/450 cm^3=1.22
9. $\alpha = V_g/V_s$=250 cm^3/450 cm^3=0.56
10. w=300 g/1200 g=0.25 or 25%
11. Θ=300 cm^3/1000 cm^3=0.30=$(w.\rho_b/\rho_w)$
12. $\Theta_\rho = V_w/V_s$=300 cm^3/450 cm^3=0.67
13. $s = V_w/V_f$=300 cm^3/550 cm^3=0.55

Example 2.5

Calculate ρ_s of a mixture containing 48% by weight of quartz, 50% of vermiculite, and 2% by weight of soil organic matter.

Solution

From Table 2.1, ρ_s is 2.65 Mg/m^3 for quartz, 2.3 Mg/m^3 for vermiculite, and 1.4 Mg/m^3 for soil organic matter. The ρ_s is computed by substituting these values in [Eq. (2.22)]:

$$\frac{1}{\rho_s} = \frac{0.48}{2.65} + \frac{0.50}{2.3} + \frac{0.02}{1.4} = 0.181 + 0.217 + 0.014 = 0.412 \frac{cm^3}{g}$$

$$\therefore \rho_s = \frac{1}{0.412} \frac{g}{cm^3} = 2.43\ g/cm^3 \text{ or } Mg/m^3$$

PROBLEMS

1. Calculate particle density of a soil from the following data:

Weight of pycnometer=50 g

Weight of the powder dry soil=214 g

Mass of soil and deaerated water when pycnometer was filled to capacity + pycnometer=352 g

Temperature of water=20°C

Volume of pycnometer=168 cm^3

2. Consider the following data based on field measurements:
i. Diameter of the cylindrical core=5.05 cm
ii. Height of the cylindrical core=5 cm
iii. Weight of the core=150 g
iv. Weight of field soil+core=312.5 g
v. Weight of the oven dried (105°C) soil+core=282.5 g
vi. Weight of the oven dried (900°C) soil+core=276.0
Using the particle density calculated in Question 1, calculate W, Θ, ρ'_b, ρ_b organic fraction, and V_s.

3. Prove or disprove the following:
i. $f = \frac{e}{1+e}$ L / = *We*
ii. $f=e+1$
iii. $e = \frac{f}{1-f}$
iv. $e=f-1$
v. $\Theta=sf$
vi. $\rho_b=V_s\rho_s+V_w\rho_w+V_a\rho_a$
vii. $V_w/V_s=\Theta(1+e)$
viii. $V_s\rho_s=\rho_b(V_s+V_w+V_a)$

4. A soil of one m^3 total volume (V_t) has the following properties:
$Vs=0.5$
$V_w=0.3$
$Va=0.2$
Assuming $\rho_s=2.65 g/cm^3$, calculate:
(a) f, f_a, s, e, M_s and ρ_b
(b) What are the weight and volume of water required to saturate it?

5. In a greenhouse study, a soil is packed in a container at a ρ_b of 1.5 Mg/m^3. The antecedent Θ is 0.2. Assuming the volume of the container is 1000 cm3, what is the volume of water needed to double the Θ of the entire soil?

6. A sample of moist soil weighed 100 g and had an oven dry moisture content (w) of 0.04. What is the oven dry weight (M_s) of the 100 g sample?

7. 10 mm of rain infiltrated a soil having an initial moisture content by volume (Θ) of 0.1 m3/m3. If the soil absorbed enough of the rainfall to raise its moisture content to 0.2 m^3/m^3, how many cm would the rainfall penetrate?

8. What are principal soil functions? Briefly describe each function.

9. How does application of soil physics improve environment quality?

10. Describe the term “sustainable use of soil and water resources.”

11. How do soil constituents influence environment quality?

12. How do soil constituents influence agricultural sustainability?

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