4

Soil Architecture and Physical Properties

And when that crop grew, and was harvested, no man had crumbled a hot clod in his fingers and let the earth sift past his fingertips.

—John Steinbeck, The Grapes of Wrath

(b)

Soil Texture
(Particle size distribution)

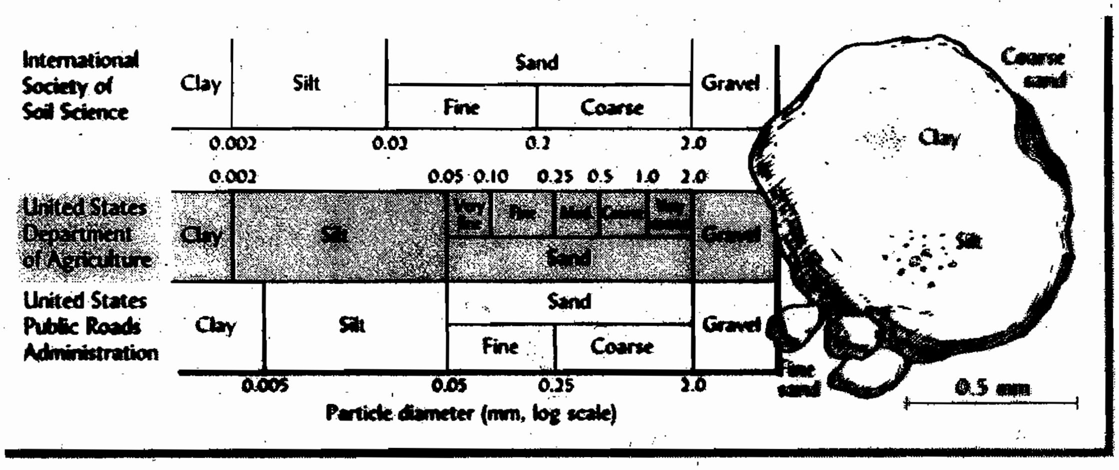


FIGURE 4.2 Classification of soil particles according to their size. The shaded scale in the center and the names on the drawings of particles follow the United States Department of Agriculture system, which is widely used throughout the world. The USDA system is also used in this book. The other two systems shown are also widely used by soil scientists and by highway construction engineers. The drawing illustrates the size of soil separates (note scale).

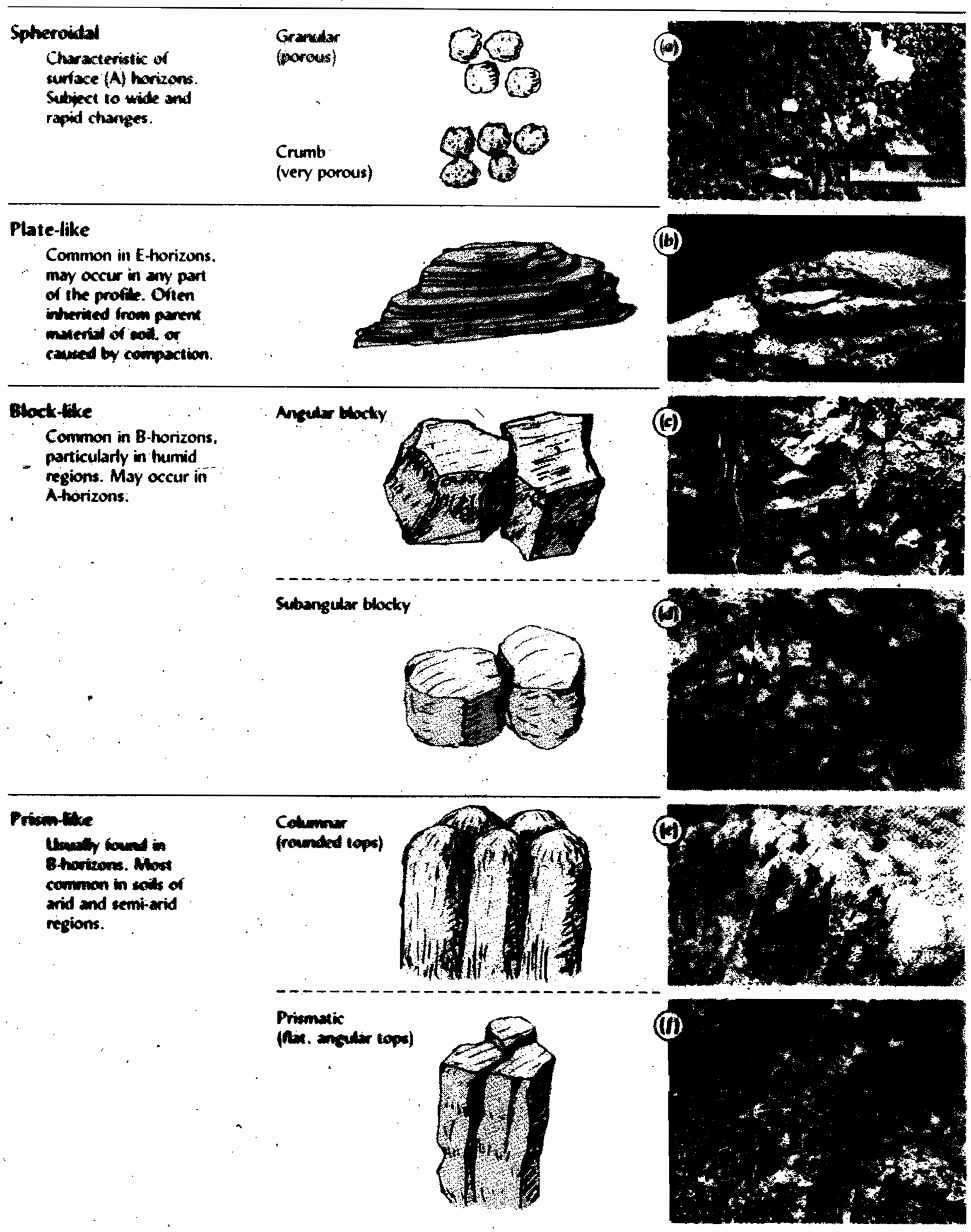
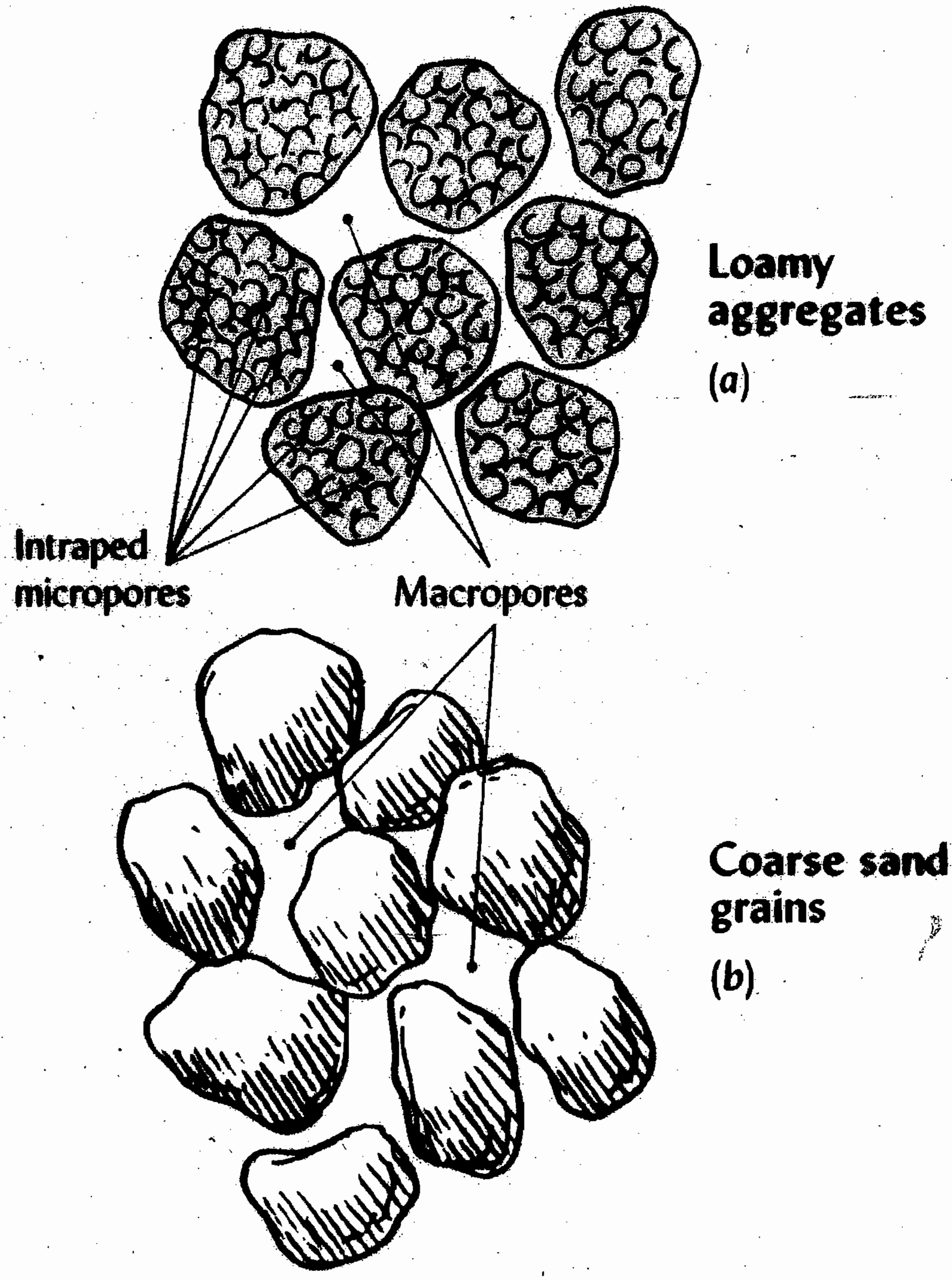


FIGURE 4.11 The various structure types (shapes) found in mineral soils. Their typical location is suggested. The drawings illustrate their essential features and the photos indicate how they look in situ. For scale, note the 15-cm-long pencil in (e) and the 3-cm-wide knife blade in (d) and (f). (Photo (e) courtesy of J. L. Arndt, now with Petersen Environmental Consulting; North Dakota State University. Others courtesy of R. Weil)

Soil Structure



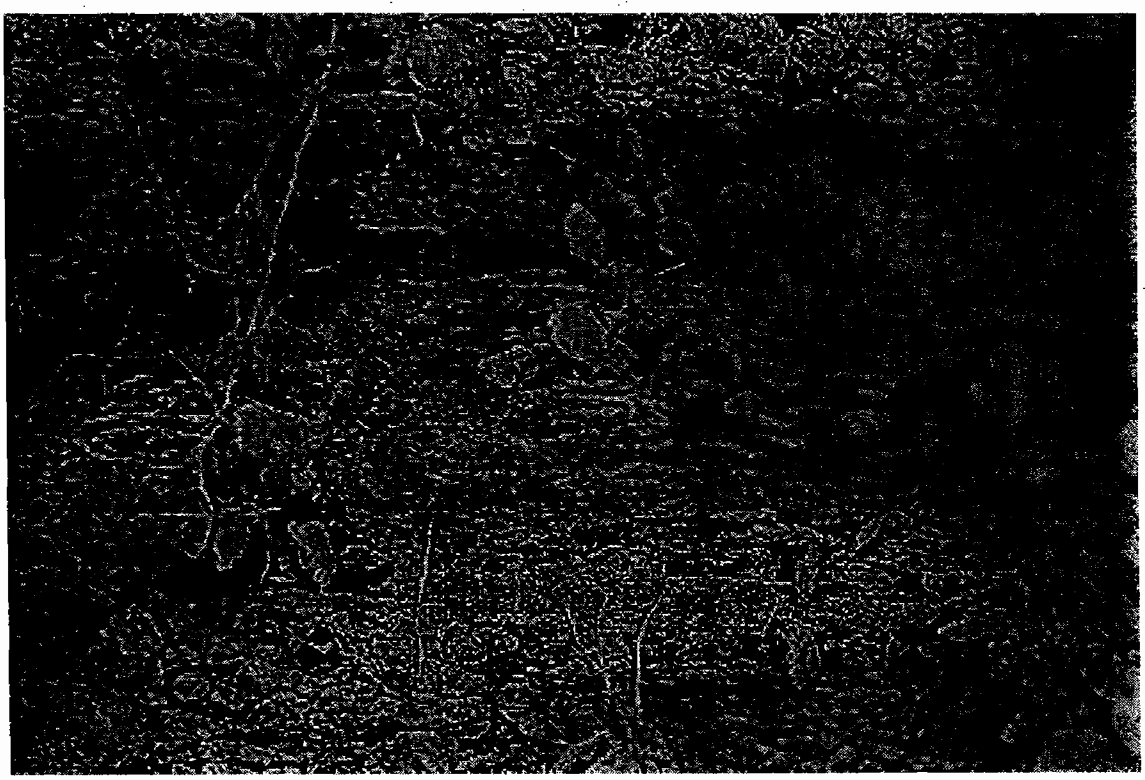
Soil Structure

Granular

- surface soils, especially with high organic carbon. Grasslands and soils worked by earthworms

Soil Structure

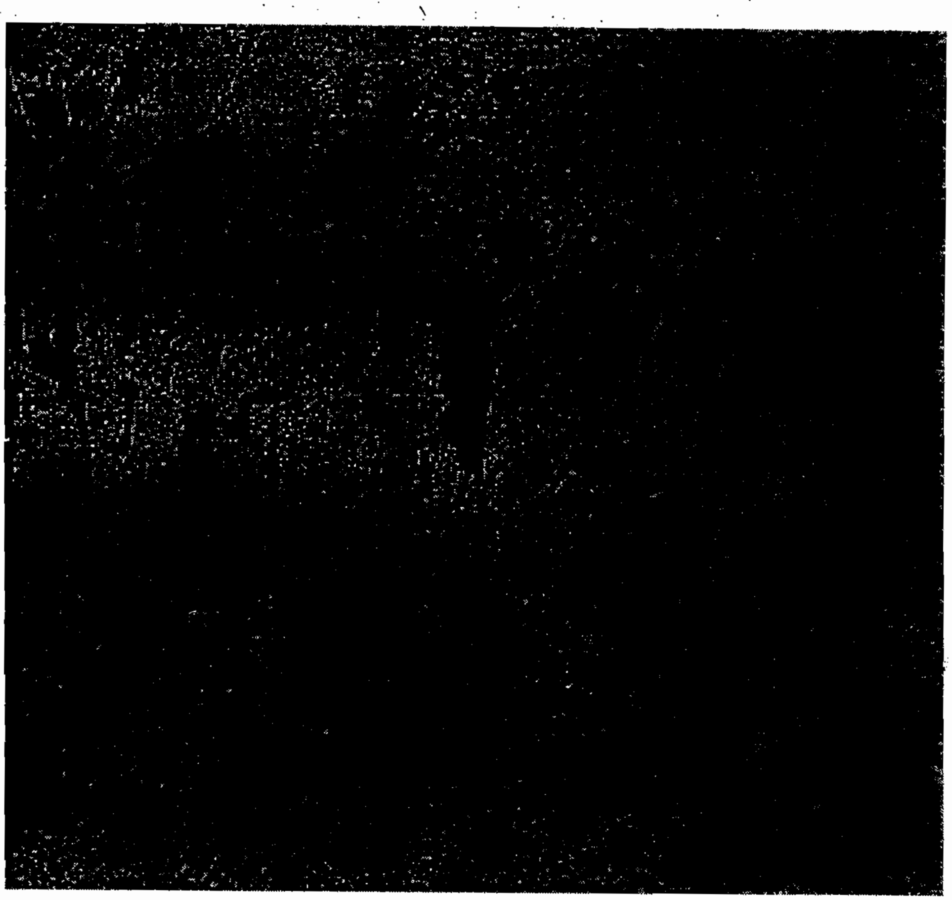
Platy



- Usually related to the structure of the parent material. Can also develop in clayey soils due to heavy machinery.

Soil Structure

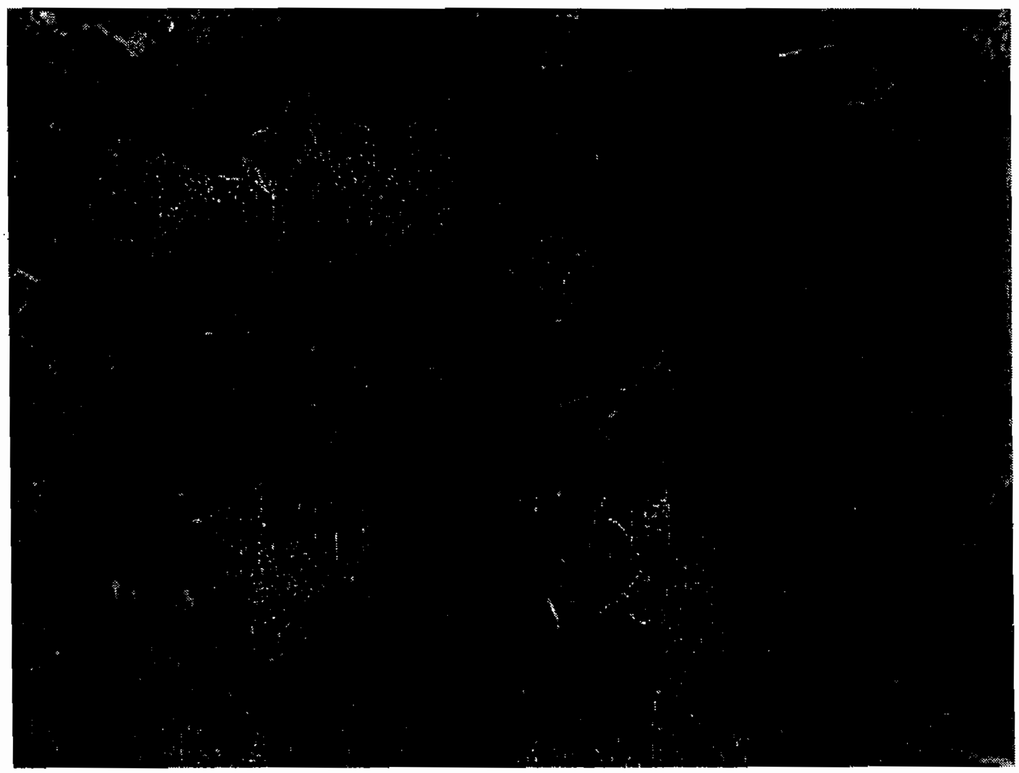
Prismatic



- Usually occur in subsoils in arid and semiarid regions. Also in poorly drained regions with swelling soil clays. Tops are angular and flat.

Soil Structure

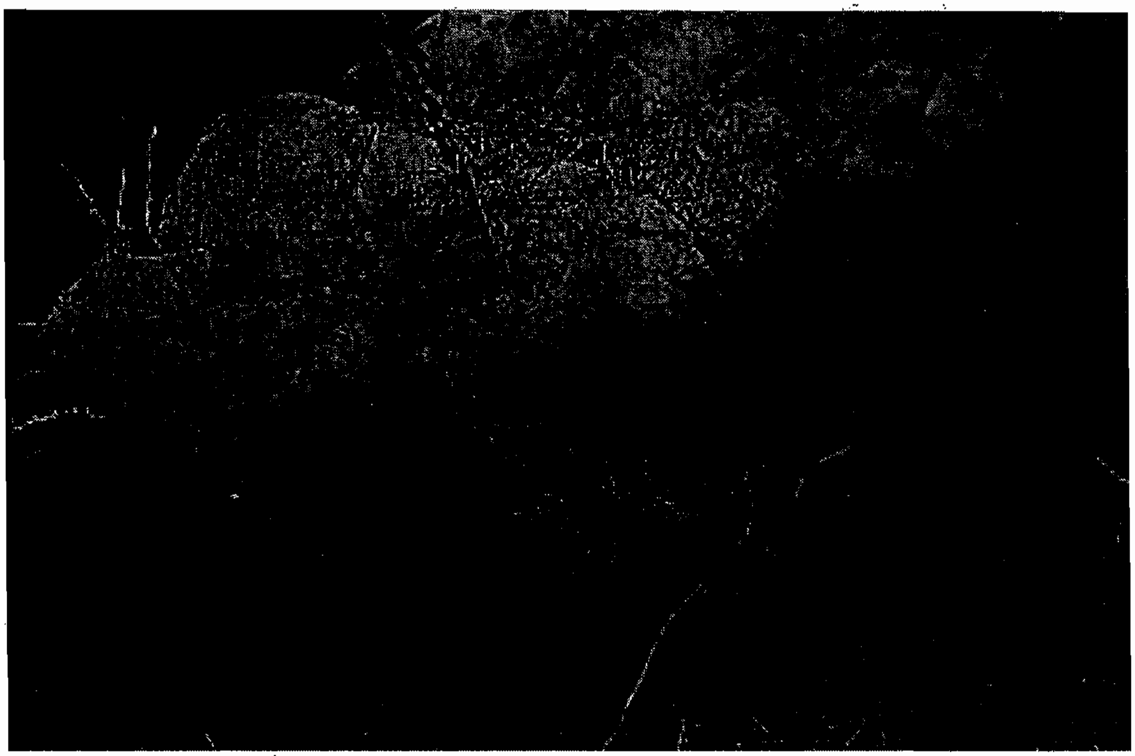
Blocky



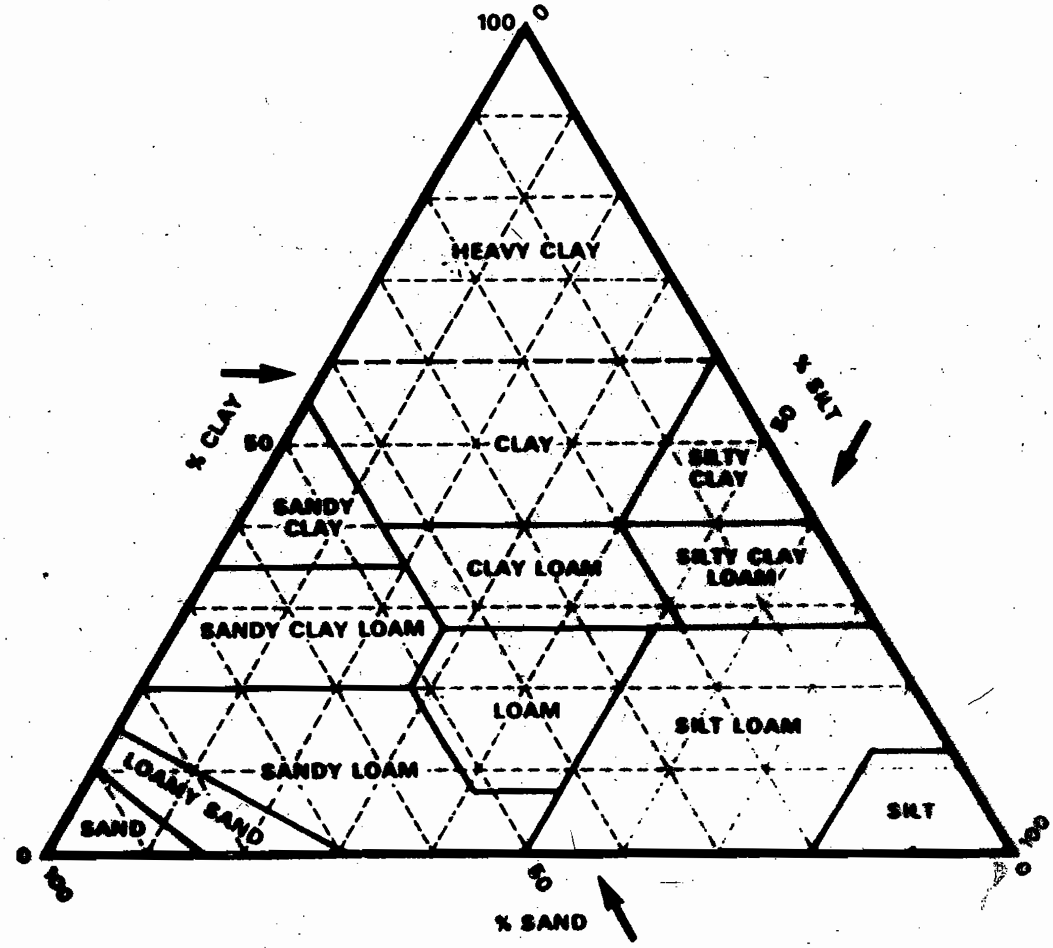
- Usually in subsoils. Related to drainage, root penetration and aeration.

Soil Structure

Columnar



- Like Prismatic except tops are rounded. Especially common in soils high in sodium.



~~Figure 1.6~~ The textural triangle.

A Method for Determining Texture by Feel

The first, and most critical, step in the texture-by-feel method is to knead a walnut-sized sample of moist soil into a uniform puttylike consistency, slowly adding water if necessary. This step may take a few minutes, but a premature determination is likely to be in error as hard clumps of clay and silt may feel like sand grains. The soil should be moist, but not quite glistening. Try to do this with only one hand so as to keep your other hand clean for writing in a field notebook (and shaking hands with your client).

While squeezing and kneading the sample, note its maleability, stickiness, and stiffness, all properties associated with the clay content. A high silt content makes a sample feel smooth and silky, with little stickiness or resistance to deformation. A soil with a significant content of sand feels rough and gritty, and makes a grinding noise when rubbed near one's ear.

Get a feel for the amount of clay by attempting to squeeze a ball of properly moistened soil between your thumb and the side of your forefinger, making a ribbon of soil. Make the ribbon as long as possible until it breaks from its own weight (see Figure 4.9).

Interpret your observations as follows:

1. Soil will not cohere into a ball, falls apart: sand
2. Soil forms a ball, but will not form a ribbon: loamy sand
3. Soil ribbon is dull and breaks off when less than 2.5 cm long and
   a. Grinding noise is audible; grittiness is prominent feel: sandy loam
   b. Smooth, floury feel prominent; no grinding audible: silt loam
   c. Only slight grittiness and smoothness; grinding not clearly audible: loam
4. Soil exhibits moderate stickiness and firmness, forms ribbons 2.5 to 5 cm long, and
   a. Grinding noise is audible; grittiness is prominent feel: sandy clay loam
   b. Smooth, floury feel prominent; no grinding audible: silty clay loam
   c. Only slight grittiness and smoothness; grinding not clearly audible: clay loam
5. Soil exhibits dominant stickiness and firmness, forms shiny ribbons longer than 5 cm, and
   a. Grinding noise is audible; grittiness is dominant feel: sandy clay
   b. Smooth, floury feel prominent; no grinding audible: silty clay
   c. Only slight grittiness and smoothness; grinding not clearly audible: clay

A more precise estimate of sand content (and hence more accurate placement in the horizontal dimension of the textural class triangle) can be made by wetting a pea-sized clump of soil in the palm of your hand and smearing it around with your finger until it your palm becomes coated with a souplike suspension of soil. The sand grains will stand out visibly and their volume as compared to the original "pea" can be estimated, as can their relative size (fine, medium, coarse etc.).

It is best to learn the method using samples of known textural class. With practice, accurate textural class determinations can be made on the spot.

(continued)

BOX 4.2 (*Cont.*) A METHOD FOR DETERMINING TEXTURE BY FEEL

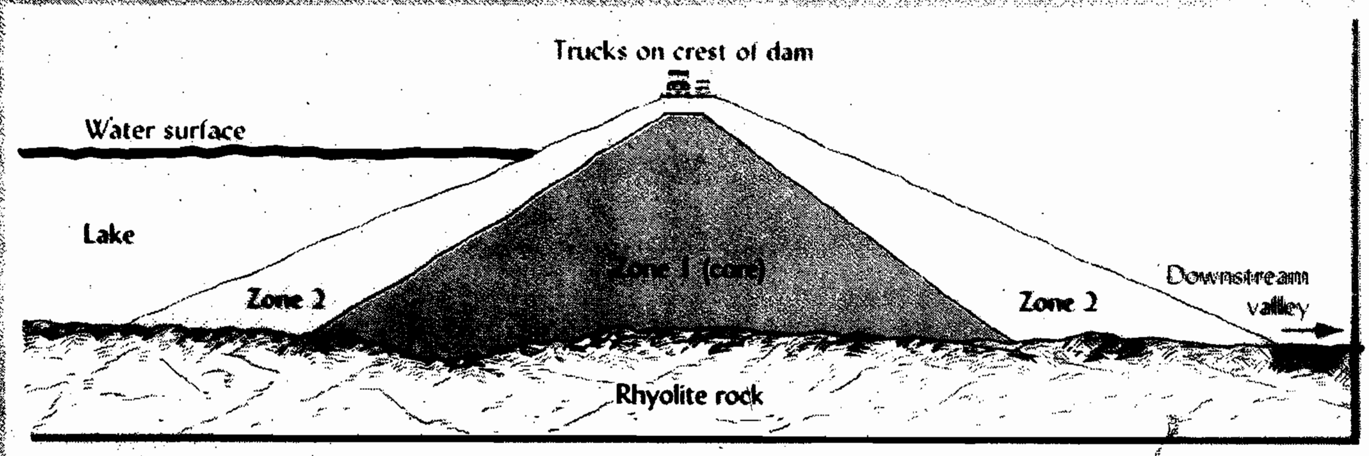
FIGURE 4.9 The "feel" method for determining soil-textural class. A moist soil sample is rubbed between the thumb and forefingers (insets) and squeezed out to make a "ribbon." *(a)* The gritty, noncohesive appearance and short ribbon of a sandy loam with about 15% clay. *(b)* The smooth, dull appearance and crumbly ribbon characteristic of a silt loam. *(c)* The smooth, shiny appearance and long, flexible ribbon of a clay. See Box 4.2 for details. (Large photos courtesy of R. Weil)

BOX 4.1 SILT AND THE FAILURE OF THE TETON DAM[a]

One of the most tragic and costly engineering failures in American history occurred in southern Idaho on 5 June 1977, less than a year after construction was completed on a large earth-fill dam across the Teton River. Eleven people were killed and 25,000 made homeless in the five hours it took to empty the 28-km-long lake that had been held in place by the dam. Some $400 million (1977 dollars) worth of damages were caused as the massive wall of water surged through the collapsed dam and the valley below. The dam failed with little warning as small seepage leaks quickly turned into raging torrents that swept away a team of bulldozers sent to make repairs.

The Teton dam was built according to a standard, time-tested design for zoned earth-fill embankments. Essentially, after [illegible] in the rhyolite rock below the soil, a core (zone 1) of tightly compacted soil material was constructed and covered with a layer (zone 2) of coarser alluvial soil material to protect it from water and wind erosion.

The core is meant to be the watertight seal that prevents water from seeping through the dam. Normally, clayey material is chosen for the core, since the sticky, plastic qualities of moist clay allow it to be compacted into a malleable, watertight mass that holds together and does not crack so long as it is kept moist. Silt, on the other hand, though it may appear similar to clay in the field, has little or no stickiness or plasticity and therefore cannot be compacted into



[illegible] as clay can. In fact, a moist mass of compacted silt will crack as it settles because it lacks plasticity. [illegible] the silt material will rapidly wash away with the flowing water, enlarging the [illegible] water to flow through, which will wash away still more of the silt. This process of rapidly [illegible] termed piping. Such piping was almost certainly a major cause of the Teton Dam failure. [illegible] zone 1 core of the dam using windblown silt deposits (termed loess—see Section 2.11) [illegible]

[illegible] lesson about the importance of texture in determining soil behavior.

[a] [illegible] the Report by the U.S. Department of Interior Teton Dam Failure Group (1977).

BOX 4.3 STOKE'S LAW IN CALCULATING PARTICLE SIZE BY SEDIMENTATION METHODS

The complete expression of Stoke's Law tells us the velocity V of a particle falling through a fluid is directly proportional to the gravitational force *g*, the difference between the density of the particle and the density of the fluid ($D_s - D_f$) and the square of the effective* particle diameter (d^2). The settling velocity is inversely proportional to the viscosity or "thickness" of the fluid η. Since velocity equals distance *h* divided by time *t* we can write Stoke's Law as:

$$V = \frac{h}{t} = \frac{d^2 g (D_s - D_f)}{18\eta}$$

Where: g = gravitational force = 9.81 Newtons per kilogram (9.81 N/kg)

η = viscosity of water at 20°C = 1/1000 Newton-seconds per m^2 (10^{-3} Ns/m^2)

D_s = density of the solid particles, for most soils = 2.65×10^3 kg/m^3

D_f = density of the fluid (i.e., water) = 1.0×10^3 kg/m^3

Substituting these values into the equation, we can write:

$$V = \frac{h}{t} = \frac{d^2 \cdot 9.81\ N/kg \cdot (2.65 \cdot 10^3\ kg/m^3 - 1.0 \cdot 10^3\ kg/m^3)}{18 \cdot 10^{-3}\ Ns/m^2}$$

$$= \frac{9.81\ N/kg \cdot 1.65 \cdot 10^3\ kg/m^3}{18 \cdot 10^{-3}\ Ns/m^2} \cdot d^2$$

$$= \frac{16.19 \cdot 10^3\ N/m^3}{0.018\ Ns/m^2} \cdot d^2$$

$$= \frac{9 \times 10^5}{sm} \cdot d^2$$

$$= kd^2$$

where $k = \frac{9 \times 10^5}{sm}$

Note that $V = kd^2$ is the same as the simplified formula given in the text.

Let's choose to sample a soil suspension at 0.1 m (10 cm) depth. We can calculate the seconds of settling time we must allow if we want the smallest silt particle to have just passed our sampling depth so our sample will contain only clay.

Chosen: $h = 0.1$ m

$d = 2 \cdot 10^{-6}$ m (0.002 mm, smallest silt)

Solving for *t* we can write:

$$\frac{h}{t} = d^2k \quad \Rightarrow \quad \frac{t}{h} = \frac{1}{d^2k} \quad \Rightarrow \quad t = \frac{h}{d^2k}$$

Therefore:

$$t = \frac{0.1\ m}{(2 \cdot 10^{-6}\ m)^2 \cdot 9 \cdot 10^5\ s^{-1}/m^{-1}}$$

$$t = 27{,}777 \text{ seconds} = 463 \text{ minutes} = 7.72 \text{ hours}$$

By comparison, the smallest sand particle (d = 0.05 mm) would make the same journey in only 44 seconds.

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*Stoke's Law applies to smooth round particles. Since most soil particles are neither smooth nor round, sedimentation techniques determine the *effective* diameters, not necessarily the actual diameter of the soil particle.

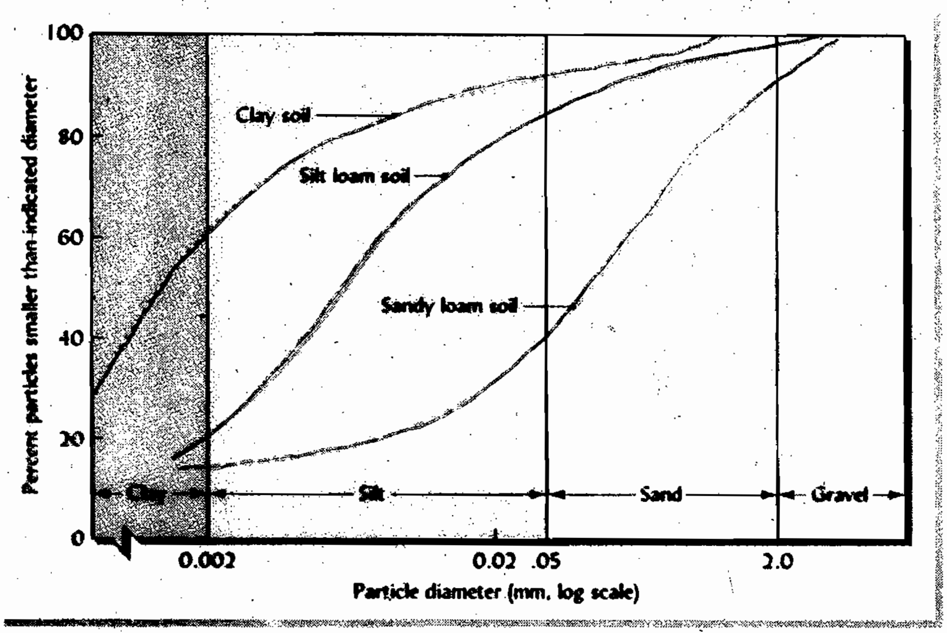
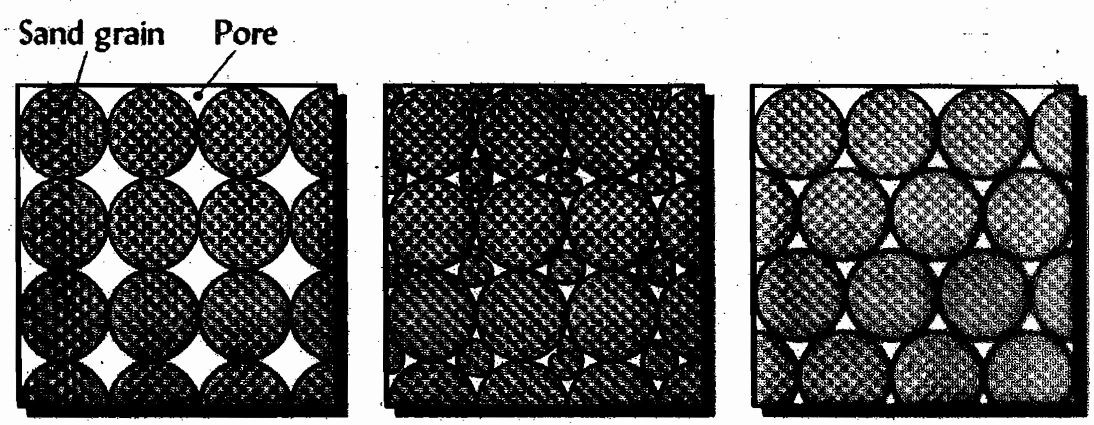


FIGURE 4.10 Particle-size distribution in three soils varying widely in their textures. Note that there is a gradual transition in the particle-size distribution in each of these soils.

Generalized Influence of Soil Separates on Some Properties and Behavior of Soils.[a]

Property/behavior	Rating associated with soil separates		
	Sand	*Silt*	*Clay*
Water-holding capacity	Low	Medium to High	High
Aeration	Good	Medium	Poor
Drainage rate	High	Slow to Medium	Very slow
Soil organic matter level	Low	Medium to High	High to Medium
Decomposition of organic matter	Rapid	Medium	Slow
Warm-up in spring	Rapid	Moderate	Slow
Compactability	Low	Medium	High
Susceptibility to wind erosion	Moderate (high if fine sand)	High	Low
Susceptibility to water erosion	Low (unless fine sand)	High	Low if aggregated, high if not
Shrink-swell potential	Very Low	Low	Moderate to very high
Sealing of ponds, dams, and landfills	Poor	Poor	Good
Suitability for tillage after rain	Good	Medium	Poor
Pollutant leaching potential	High	Medium	Low (unless cracked)
Ability to store plant nutrients	Poor	Medium to high	High
Resistance to pH change	Low	Medium	High

[a] Exceptions to these generalizations do occur, especially as a result of soil structure and clay minerology.



Well sorted, loose packing (*a*)

Well graded, loose packing (*b*)

Well sorted, tight packing (*c*)

Soil Mass and Volume Relations

PARTICLE DENSITY (MEAN DENSITY OF SOLIDS) ρ_s

$$\rho_s = M_s / V_s$$

In most mineral soils, the mean density of the particles is about 2.6-2.7 gm/cm^3, close to the density of quartz

DRY BULK DENSITY ρ_b

$$\rho_b = M_s / V_T = M_s / (V_s + V_a + V_w)$$

The dry bulk density expresses the ratio of the mass of dried soil to its total volume (solids and pores together).

In sandy soils, ρ_b can be as high as 1.6, whereas in aggregated loams and in clay soils, it can be as low as 1.1 gm/cm^3.

The bulk density is affected by the structure of the soil, i.e., its looseness or degree of compaction, as well as by its swelling and shrinkage characteristics, which are dependent upon clay content and wetness.

POROSITY n

$$n = V_v / V_T = (V_a + V_w)/(V_s + V_a + V_w)$$

The porosity is an index of the relative pore volume in the soil. Its value generally lies in the range 0.3-0.6 (30-60%). Coarse-textured soils tend to be less porous than fine-textured soils, though the mean size of individual pores is greater in coarse-textured soils.

In clayey soils, the porosity is highly variable as the soil alternately swells, shrinks, aggregates, disperses, compacts, and cracks.

The total porosity, in any case, reveals nothing about the *pore size distribution,* which is itself an important property to be discussed in a later in the course.

VOID RATIO *e*

$$e = (V_a + V_w)/ V_s = V_v /(V_T - V_v) = \frac{V_v}{V_s}$$

The void ratio is also an index of the fractional volume of soil pores, but it relates that volume to the volume of solids rather than to the total volume of soil.

Void ratio is the generally preferred index in soil engineering and mechanics, whereas porosity is the more frequently used index in agricultural soil physics. Generally, e varies between 0.3 and 2.0.

SOIL WETNESS

The wetness, or relative water content, of the soil can be expressed in various ways: relative to the mass of solids, relative to the total volume, and relative to the volume of pores. The various indexes are defined as follows:

Mass Water Content θ_m

$$\theta_m = M_w / M_s$$

This is the mass of water relative to the mass of dry soil particles, often referred to as the *gravimetric water content*.

The term *dry soil* is generally defined as a soil dried to equilibrium in an oven at 105 C. In a mineral soil that is saturated, θ_m can range between 25 and 60% depending on the bulk density.

The saturated water content is generally higher in clayey than in sandy soils. In the case of organic soils, such as peat or muck, the saturated water content on the mass basis may exceed 100%.

Volumetric Water Content θ_v

$$\theta_v = V_w/V_T = V_w/(V_s + V_v)$$

In sandy soils, the value of θ_v at saturation is on the order of 40-50%; in medium-textured soils, it is approximately 50%; and in clayey soils, it can approach 60%.

In the latter, the relative volume of water at saturation can exceed the porosity of the dry soil, since clayey soils swell upon wetting.

The use of θ_v rather than of θ_m to express water content is often more convenient because it is more directly adaptable to the computation of fluxes and water quantities added to soil by irrigation or rain and to quantities subtracted from the soil by evapotranspiration or drainage. This is because θ_v also represents the depth ratio of soil water, i.e., the depth of water per unit depth of soil.

Degree of Saturation S

$$S = V_w/V_v$$

This index expresses the volume of water present in the soil relative to the volume of pores. The index *S* ranges from zero in dry soil to unity (or 100%) in a completely saturated soil.

However, complete saturation is seldom attained in soils, since some air is nearly always present and may become trapped in a very wet soil.

AIR-FILLED POROSITY (FRACTIONAL AIR CONTENT) n_a

$$n_a = V_a/V_T = V_a / (V_s + V_a + V_w)$$

This is a measure of the relative air content of the soil, and as such is an important criterion of soil aeration.

(modified from Hillel (1980))

Example calculation of bulk density, porosity, void ratio, mass water content, volumetric water content, degree of saturation and air-filled porosity.

A sample of moist soil having a wet mass of 1000 gm and a volume of 640cm^3 was dried in an oven at 105 C and found to have a dry mass of 800 gm. Assuming the typical value of particle density for a mineral soil, calculate the bulk density, porosity, void ratio, mass water content, volumetric water content, degree of saturation, and air-filled porosity.

Bulk density (ρ_b)

$$\rho_b = \frac{M_s}{V_T} = \frac{800g}{640cm^3} = 1.25\ g/cm^3$$

Porosity (n)

$$n = \frac{V_v}{V_T} = \frac{V_T - V_s}{V_T}$$

$$V_s = \frac{M_s}{\rho_s} = \frac{800g}{2.65\ g/cm^3} = 301.9\ cm^3$$

$$n = \frac{640cm^3 - 301.9cm^3}{640cm^3} = 0.528 \rightarrow 52.8\%$$

Void Ratio (e)

$$e = \frac{V_v}{V_s} = \frac{V_T - V_s}{V_s} = \frac{640cm^3 - 301.9cm^3}{301.9cm^3} = 1.12$$

Mass water content θ_m

$$\theta_m = \frac{M_w}{M_s} = \frac{M_T - M_s}{M_s} = \frac{1000g - 800g}{800g} = 0.25 \rightarrow 25\%$$

Volumetric Water content θ_v

$$\theta_v = \frac{V_w}{V_T} = \frac{200cm^3}{640cm^3} = 0.3125 \Rightarrow 31.25\%$$

degree of saturation (S)

$$S = \frac{V_w}{V_v} = \frac{V_w}{V_T - V_s} = \frac{200cm^3}{640cm^3 - 301.9cm^3} = 0.592 \rightarrow 59.2\%$$

Air-filled porosity (n_a)

$$n_a = \frac{V_a}{V_T} = \frac{V_T - V_w - V_s}{V_T} = \frac{(640 - 200 - 301.9)cm^3}{640cm^3} = 0.216 \rightarrow 21.6\%$$

Additional Mass and Volume Relations

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

$$e = \frac{n}{1-n} \qquad n = \frac{e}{1+e}$$

2. Volumetric Water Content (θ_v) and Saturation (S)

$$\theta_v = nS \qquad S = \frac{\theta_v}{n}$$

3. Porosity (n) and Bulk Density (ρ_s)

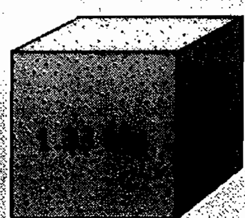
$$n = \frac{(\rho_s - \rho_b)}{\rho_s} = 1 - \frac{\rho_b}{\rho_s}$$

$$\rho_b = (1-n)\rho_s$$

4. Mass water Content (θ_m) and Volumetric Water Content (θ_v)

$$\theta_v = \theta_m \frac{\rho_b}{\rho_w} \qquad \theta_m = \theta_v \frac{\rho_w}{\rho_b}$$

In the field, one cubic meter of a certain soil appears as...



To calculate bulk density of the soil:

Volume = 1 m^3 (solids + pores) Weight = 1.33 Mg (solids only)

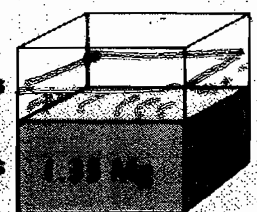
$$\text{Bulk density} = \frac{\text{Weight of oven dry soil}}{\text{Volume of soil (solids + pores)}}$$

Therefore

$$\text{Bulk density, } D_b = \frac{1.33}{1} = 1.33 \text{ Mg/m}^3$$

ρ_b

If all the solids were compressed to the bottom, the cube would look like...



To calculate solid particle density:

Volume = 0.5 m^3 (solids only) Weight = 1.33 Mg (solids only)

$$\text{Solid particle density} = \frac{\text{Weight of solids}}{\text{Volume of solids}}$$

Therefore

$$\text{Solid particle density, } D_p = \frac{1.33}{0.5} = 2.66 \text{ Mg/m}^3$$

ρ_s

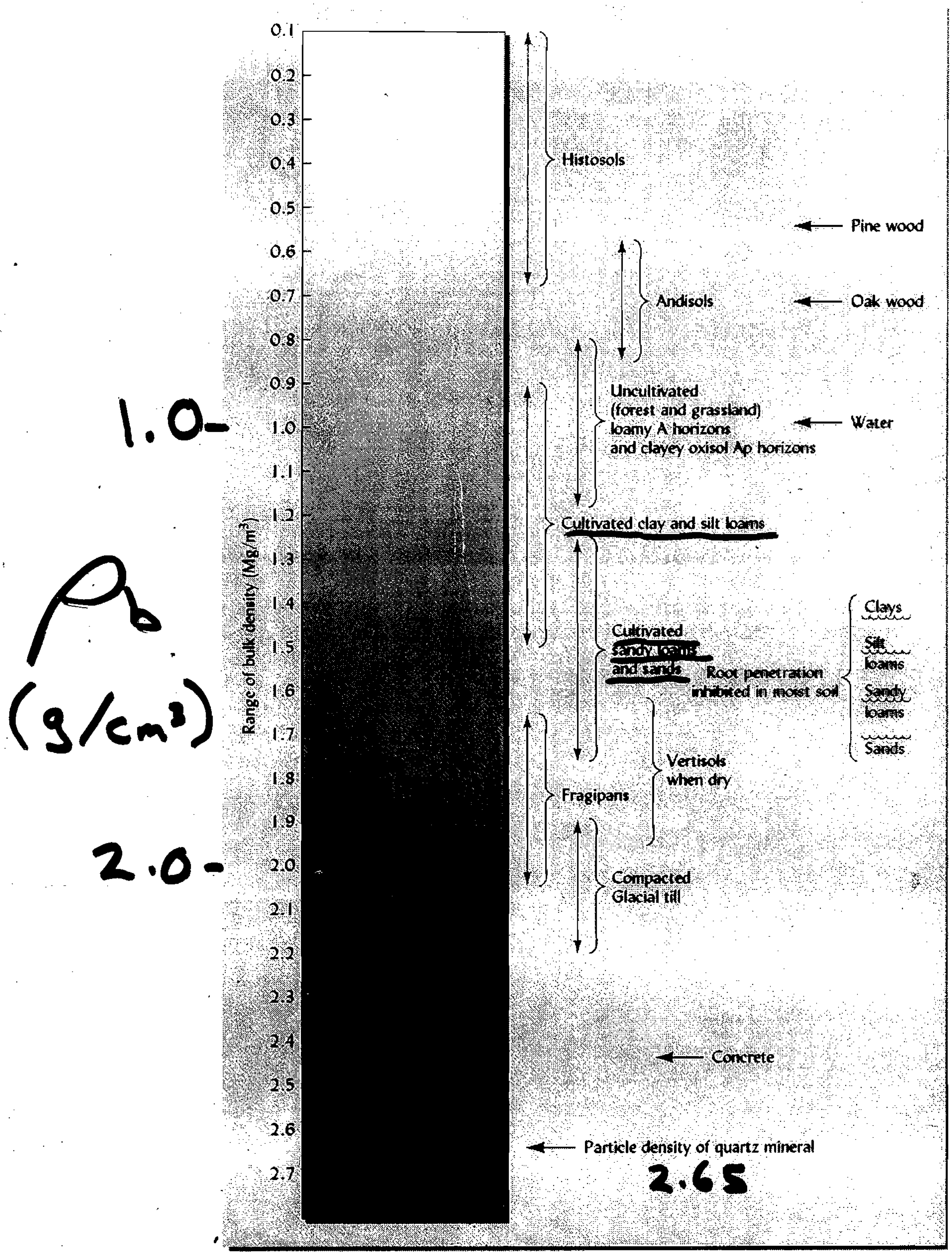


FIGURE 4.15 Bulk densities typical of a variety of soils and soil materials.

TABLE 4.5 **A Size Classification of Soil Pores and Some Functions of Each Size Class**

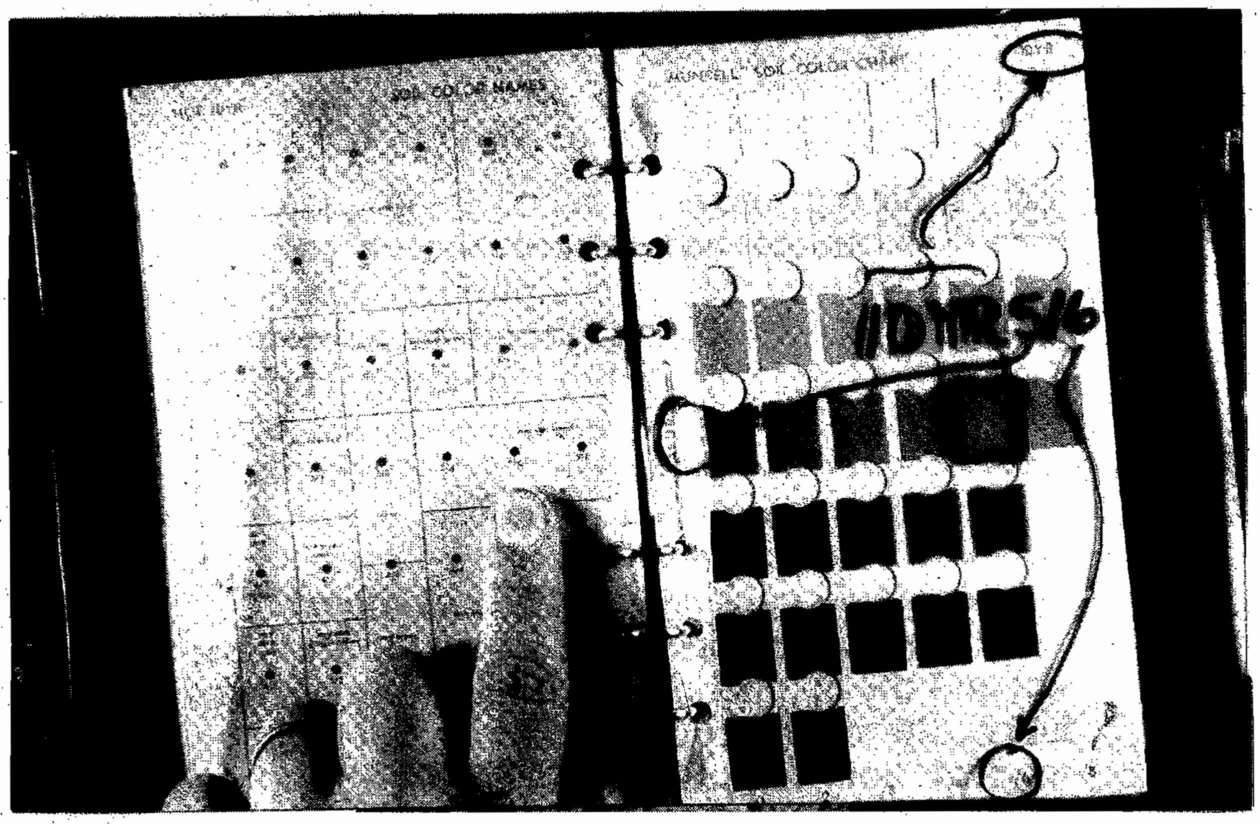
Pore sizes are actually a continuum and the boundaries between classes given here are inexact and somewhat arbitrary. The term micropore *is often broadened to refer to all the pores smaller than macropores.*

Simplified class	*Class*[a]	*Effective diameter range (mm)*	*Characteristics and functions*
Macropores	Macropores	0.08–5+	Generally found between soil peds (interped); water drains by gravity; effectively transmit air; large enough to accommodate plant roots, habitat for certain soil animals.
Micropores	Mesopores	0.03–0.08	Retain water after drainage; transmit water by capillary action, accommodate fungi and root hairs.
	Micropores	0.005–0.03	Generally found within peds (intraped); retain water that plants can use; accommodate most bacteria.
	Ultramicropores	0.0001–0.005	Found largely with clay groupings; retain water that plants cannot use; exclude most microorganisms.
	Cryptopores	<0.0001	Exclude all microorganisms, too small for large molecules to enter.

[a] The pore size classes and boundary diameters are those of Brewer, 1964 as cited in Soil Sci. Soc. Amer. (1996).

Soil Colour

Standardised Munsell Color Book



See plates between p. 82 - 83
in Text