Soil Moisture and Groundwater Recharge

The *porosity* of the soil is the percent of void space.

$$n = 100(V_v/V)$$

where

n is porosity (percentage)
V_v is volume of the void space (L^3; cm^3 or m^3)
V is volume of the sample (L^3; cm^3 or m^3)

The *void ratio* of the soil is the ratio of the volume of the voids to the volume of the

$$e = V_v/V_s$$

where

e is void ratio (dimensionless)
V_s is volume of the solids (L^3; cm^3 or m^3)

Porosity and Void Ratio

The total volume is equal to the volume of the voids plus the volume of the soli

$$V = V_v + V_s$$

The void ratio is closely related to the porosity if porosity is expressed as a ratio

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

and

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

Water Content and Saturation Ratio

The *gravimetric water content* of the soil is the mass of the contained water divid the mass of the solid particles (dry mass of soil):

$$\theta_g = 100(W_w/W_s)$$

where

θ_g is the gravimetric water content (percentage)
W_w is the mass of the water in the soil (M; g or kg)
W_s is the mass of the solid particles (M; g or kg)

The *volumetric water content* of the soil is the volume of the contained water divic the total volume of the soil:

$$\theta_v = V_w/V$$

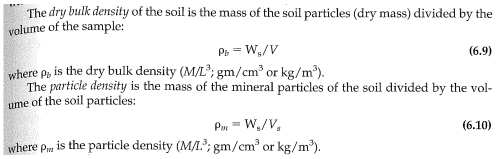
where

θ_v is the volumetric water content (dimensionless ratio)
V_w is the volume of the contained water (L^3; cm^3 or m^3)

The **saturation ratio** of a soil is the volume of the contained water divided by th ume of the voids:

$$R_s = V_w/V_v$$

Bulk Density and Particle Density



The *dry bulk density* of the soil is the mass of the soil particles (dry mass) divided by the volume of the sample:

$$\rho_b = W_s/V \tag{6.9}$$

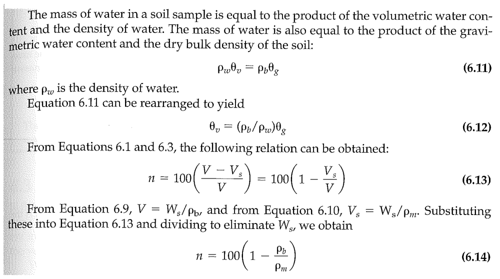
where ρ_b is the dry bulk density (M/L^3; gm/cm^3 or kg/m^3).

The *particle density* is the mass of the mineral particles of the soil divided by the volume of the soil particles:

$$\rho_m = W_s/V_s \tag{6.10}$$

where ρ_m is the particle density (M/L^3; gm/cm^3 or kg/m^3).

Porosity from Density



The mass of water in a soil sample is equal to the product of the volumetric water content and the density of water. The mass of water is also equal to the product of the gravimetric water content and the dry bulk density of the soil:

$$\rho_w\theta_v = \rho_b\theta_g \tag{6.11}$$

where ρ_w is the density of water.

Equation 6.11 can be rearranged to yield

$$\theta_v = (\rho_b/\rho_w)\theta_g \tag{6.12}$$

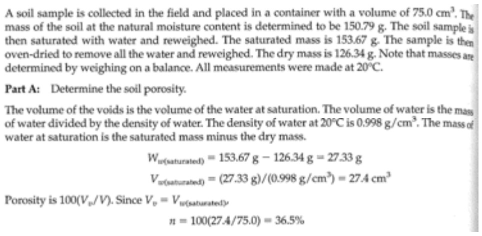
From Equations 6.1 and 6.3, the following relation can be obtained:

$$n = 100\left(\frac{V - V_s}{V}\right) = 100\left(1 - \frac{V_s}{V}\right) \tag{6.13}$$

From Equation 6.9, $V = W_s/\rho_b$, and from Equation 6.10, $V_s = W_s/\rho_m$. Substituting these into Equation 6.13 and dividing to eliminate W_s, we obtain

$$n = 100\left(1 - \frac{\rho_b}{\rho_m}\right) \tag{6.14}$$

Example



A soil sample is collected in the field and placed in a container with a volume of 75.0 cm^3. The mass of the soil at the natural moisture content is determined to be 150.79 g. The soil sample is then saturated with water and reweighed. The saturated mass is 153.67 g. The sample is then oven-dried to remove all the water and reweighed. The dry mass is 126.34 g. Note that masses are determined by weighing on a balance. All measurements were made at 20°C.

Part A: Determine the soil porosity.

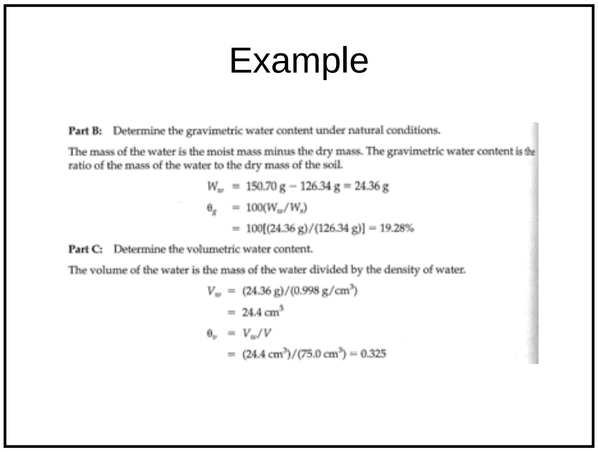
The volume of the voids is the volume of the water at saturation. The volume of water is the mass of water divided by the density of water. The density of water at 20°C is 0.998 g/cm^3. The mass of water at saturation is the saturated mass minus the dry mass.

$$W_{w(\text{saturated})} = 153.67\text{ g} - 126.34\text{ g} = 27.33\text{ g}$$

$$V_{w(\text{saturated})} = (27.33\text{ g})/(0.998\text{ g/cm}^3) = 27.4\text{ cm}^3$$

Porosity is $100(V_v/V)$. Since $V_v = V_{w(\text{saturated})}$,

$$n = 100(27.4/75.0) = 36.5\%$$



Example

Part B: Determine the gravimetric water content under natural conditions.

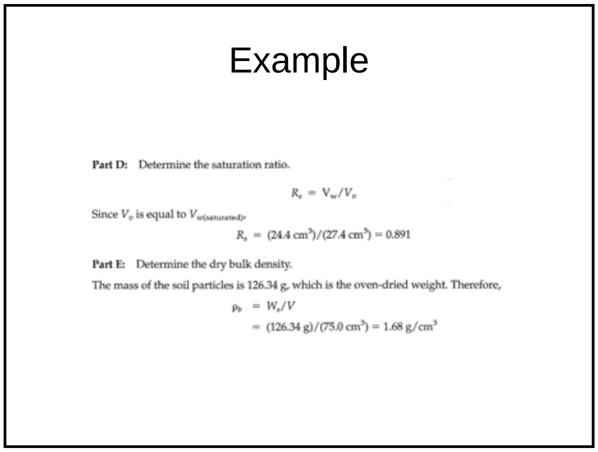
The mass of the water is the moist mass minus the dry mass. The gravimetric water content is the ratio of the mass of the water to the dry mass of the soil.

$$
\begin{aligned}
W_w &= 150.70\text{ g} - 126.34\text{ g} = 24.36\text{ g} \\
\theta_g &= 100(W_w/W_s) \\
&= 100[(24.36\text{ g})/(126.34\text{ g})] = 19.28\%
\end{aligned}
$$

Part C: Determine the volumetric water content.

The volume of the water is the mass of the water divided by the density of water.

$$
\begin{aligned}
V_w &= (24.36\text{ g})/(0.998\text{ g/cm}^3) \\
&= 24.4\text{ cm}^3 \\
\theta_v &= V_w/V \\
&= (24.4\text{ cm}^3)/(75.0\text{ cm}^3) = 0.325
\end{aligned}
$$



Example

Part D: Determine the saturation ratio.

$$R_s = V_w/V_v$$

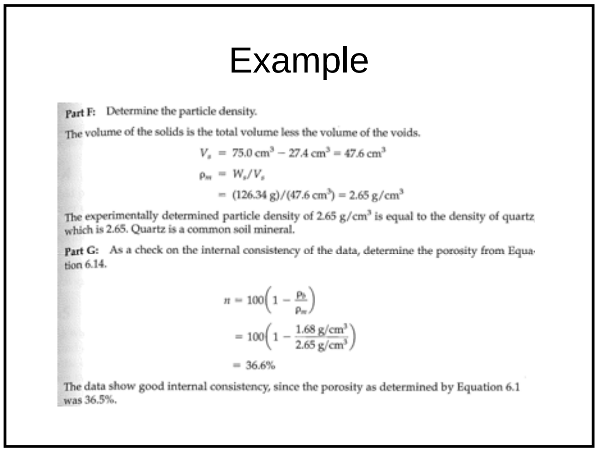
Since V_v is equal to $V_{w(\text{saturated})}$,

$$R_s = (24.4\text{ cm}^3)/(27.4\text{ cm}^3) = 0.891$$

Part E: Determine the dry bulk density.

The mass of the soil particles is 126.34 g, which is the oven-dried weight. Therefore,

$$
\begin{aligned}
\rho_b &= W_s/V \\
&= (126.34\text{ g})/(75.0\text{ cm}^3) = 1.68\text{ g/cm}^3
\end{aligned}
$$



Example

Part F: Determine the particle density.

The volume of the solids is the total volume less the volume of the voids.

$$
\begin{aligned}
V_s &= 75.0\text{ cm}^3 - 27.4\text{ cm}^3 = 47.6\text{ cm}^3 \\
\rho_m &= W_s/V_s \\
&= (126.34\text{ g})/(47.6\text{ cm}^3) = 2.65\text{ g/cm}^3
\end{aligned}
$$

The experimentally determined particle density of 2.65 g/cm^3 is equal to the density of quartz which is 2.65. Quartz is a common soil mineral.

Part G: As a check on the internal consistency of the data, determine the porosity from Equation 6.14.

$$
\begin{aligned}
n &= 100\left(1 - \frac{\rho_b}{\rho_m}\right) \\
&= 100\left(1 - \frac{1.68\text{ g/cm}^3}{2.65\text{ g/cm}^3}\right) \\
&= 36.6\%
\end{aligned}
$$

The data show good internal consistency, since the porosity as determined by Equation 6.1 was 36.5%.

Origin of Surface Tension

Water molecules in a liquids interior are attracted in all directions…

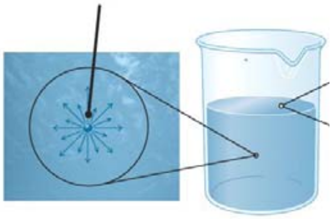


Fig. 16.13

Origin of Surface Tension

Water molecules in a liquids interior are attracted in all directions…

…whereas surface molecules have a net inward attraction that results in surface tension…

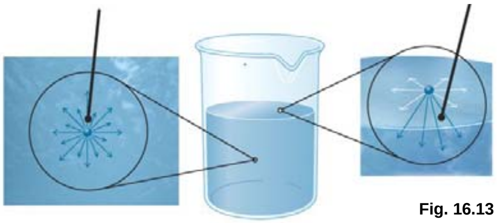


Fig. 16.13

…that acts like a membrane, allowing objects to float.

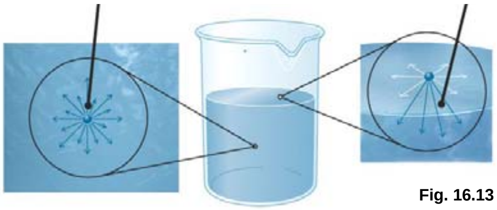
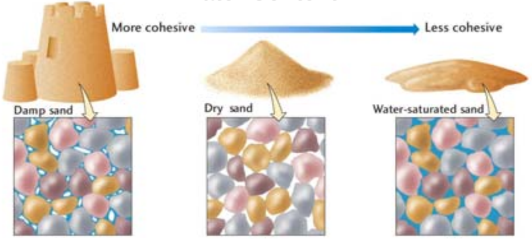


Fig. 16.13

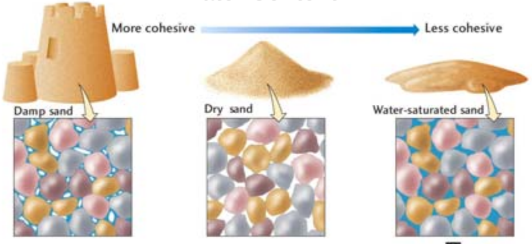
Mass Movement Depends on Water Content



Surface tension in damp sand increases cohesion

Fig. 16.13

Mass Movement Depends on Water Content

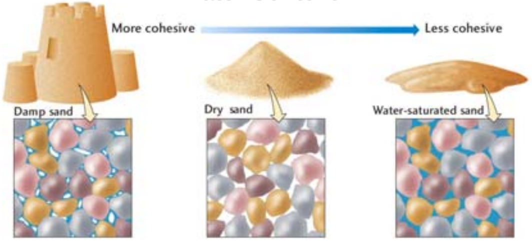


Surface tension in damp sand increases cohesion

Dry sand is bound only by friction

Fig. 16.13

Mass Movement Depends on Water Content



Surface tension in damp sand increases cohesion

Dry sand is bound only by friction

Saturated sand flows easily because of interstitial water

Fig. 16.13

Capillary Forces

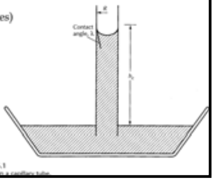
In a tube of small diameter, the free-water surface will assume a shape with the minimum surface area. The attraction of the solid for the liquid will draw the liquid up into the tube. The upward force will eventually be offset by the weight of the column of water. The water, itself, is under tension; thus, the pressure is less than atmospheric. Figure 6.1 shows the rise of a fluid in a glass capillary due to **capillary forces.** The fluid meets the glass capillary wall at a contact angle.

The rise of a fluid in a capillary tube is given by

$$h_c = \frac{2\sigma\cos\lambda}{\rho_w g R} \qquad \textbf{(6.15)}$$

where

h_c is the height of the capillary rise (L; cm or m)
σ is the surface tension of the fluid (M/T^2; g/s^2 or kg/s^2)
λ is the angle of the meniscus with the capillary tube (degrees)
ρ_w is the density of the fluid (M/L^3; g/cm^3 or kg/m^3)
g is the acceleration of gravity (L/T^2; cm/s^2 or m/s^2)
R is the radius of the capillary tube (L; cm or m)



▲ FIGURE 6.1
Rise of water in a capillary tube

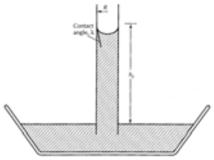
Capillary Forces

Compute the rise of water in a glass capillary tube.

For water at 18°C, the surface tension is 73 g/s^2, the density is 0.999 g/cm^3, and the contact angle may be taken as 0°.

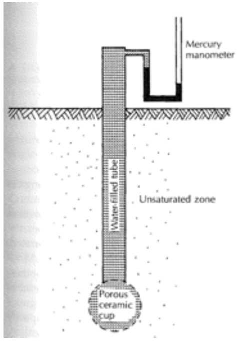
$$h_c = \frac{2 \times 73\ \text{g/s}^2 \times \cos 0^\circ}{0.999\ \text{g/cm}^3 \times 980\ \text{cm/s}^2 \times R\ \text{cm}} \qquad \textbf{(6.16)}$$

$$= \frac{0.15}{R}\ \text{cm}$$



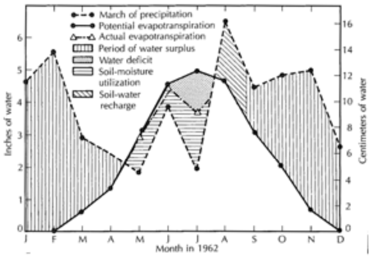
▲ FIGURE 6.1
Rise of water in a capillary tube.

Measuring Pressure in Capillary Fringe



◄ FIGURE 6.2
Porous-cup tensiometer with mercury manometer to measure soil-moisture tension.

Soil Moisture Budget



▲ FIGURE 6.3
Soil-moisture budget for Bridgehampton, New York. The diagram is based on measured precipitation and computed potential and actual evapotranspiration. The Thornthwaite method was used for evapotranspiration computations. *Source: C. W. Fetter, Jr.,* Bulletin, Geological Society of America 87 *(1976): 401–6. Used with permission.*

Moisture Content Versus Time

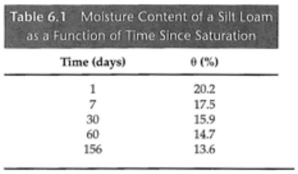
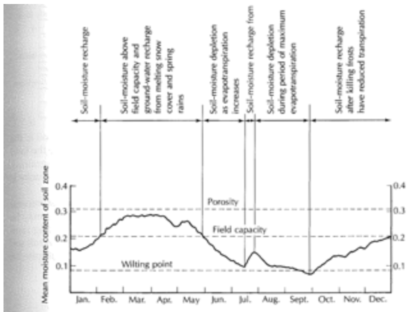


Table 6.1 Moisture Content of a Silt Loam as a Function of Time Since Saturation

Time (days)	θ (%)
1	20.2
7	17.5
30	15.9
60	14.7
156	13.6

Source: Hillel (1971).

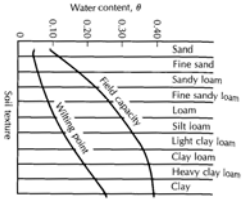
Moisture Content Versus Time



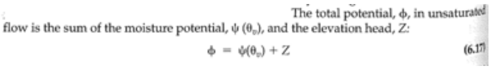
▲ FIGURE 6.4
Hypothetical fluctuation of soil moisture for a sandy loam soil through an annual cycle in a region with a moderate amount of rainfall (20 to 30 in. (50 to 75 cm) per year) and heavy rains in the spring.

Wilting Point and Field Capacity

► FIGURE 6.5
Water-holding properties of soils based on texture. The available water supply for a soil is the difference between field capacity and wilting point. *Source: U.S. Department of Agriculture,* Yearbook. *1955.*

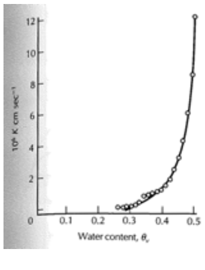


Potential in Unsaturated Flow


The total potential, ϕ, in unsaturated flow is the sum of the moisture potential, $\psi\ (\theta_v)$, and the elevation head, Z:

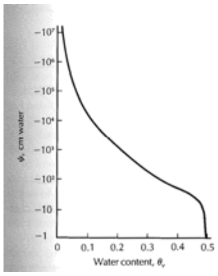
$$\phi = \psi(\theta_v) + Z \qquad (6.17)$$

K varies with moisture content



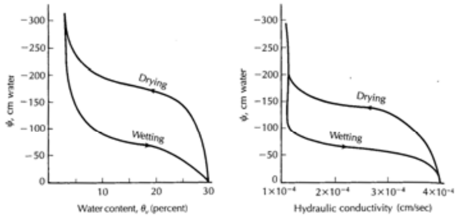
◄ FIGURE 6.6
The relationship between hydraulic conductivity, *K*, and volumetric water content, θ_w, for a clay. *Source: J. R. Philip, "Theory of Infiltration." In* Advances in Hydroscience, *vol. 5, ed. V. T. Chow. (New York: Academic Press, 1969). Used with permission.*

Moisture Potential and Water Content



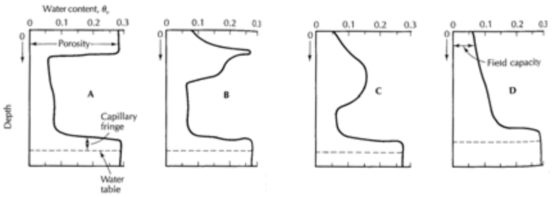
◄ FIGURE 6.7
The relationship between moisture potential, ψ, and volumetric water content, θ_v, for the clay soil of Figure 6.7. *Source: J. R. Philip, "Theory of Infiltration." In* Advances in Hydroscience, *vol. 5, ed. V. T. Chow. (New York: Academic Press, 1969). Used with permission.*

Hysteresis: Path Dependence



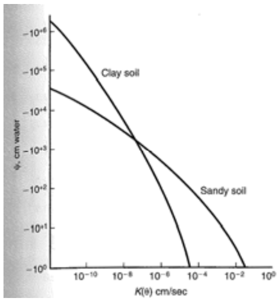
▲ FIGURE 6.8
Idealized curves showing relationships of volumetric water content, θ_w, hydraulic conductivity, *K*, and soil-moisture tension head, ψ. The effect is included for wetting and drying cycles.

Downward Movement of Water in Unsaturated Zone



► FIGURE 6.9
Moisture profiles showing the downward passage of a wave of infiltrated water. The soil is saturated at a water content of 0.29 and has a field capacity water content of 0.06.

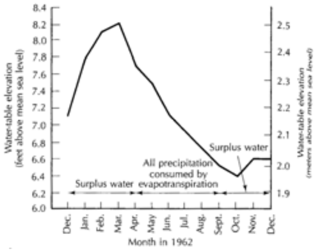
Crossover Effect

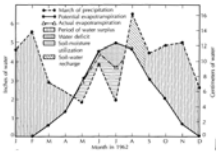


◄ FIGURE 6.10
Typical soil-moisture-potential—hydraulic-conductivity curves for a sandy soil showing the crossover effect for increasing moisture potential (decrease in water content.)

Water Table Versus Season

► FIGURE 6.11
Hydrograph of a shallow well in a water-table aquifer in Long Island. The period of record is the same as for the soil-moisture budget diagram of Figure 6.3.

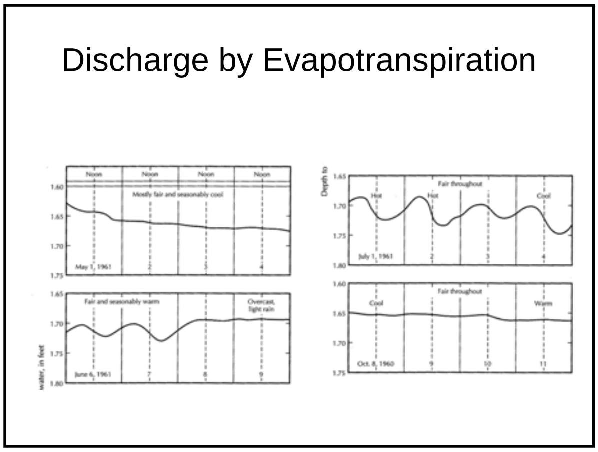




▲ FIGURE 6.3
Soil-moisture budget for Bridgehampton, New York. The diagram is based on measured precipitation and computed potential and actual evapotranspiration. The Thornthwaite method was used for evapotranspiration computations. Source: C. W. Fetter, Jr., Bulletin, Geological Society of America 87 (1976): 401–6. Used with permission.

Longer Term Trends

▲ FIGURE 6.12
Monthly hydrograph of water levels in a water-table monitoring well on eastern Long Island, New York.



Discharge by Evapotranspiration