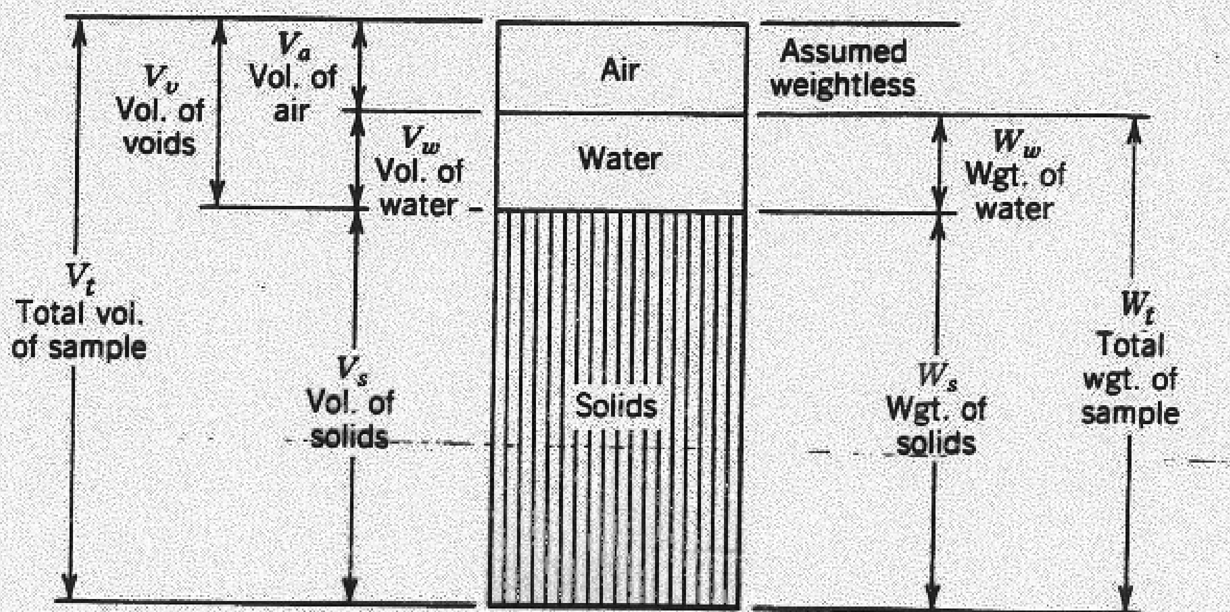

Figure 8. Phase Diagram Representing the Different Phases in a Rock. (after Johnson and DeGraff, 1988)

$\rho = \frac{M}{V}$ $\gamma = \rho g$

$n = \frac{V_v}{V}$ $\rho_d = \frac{M_s}{V}$ $\rho_{sat} = \frac{M_{sat}}{V}$

$w = \frac{M_w}{M_s}$

Table 10.1. Some values of the common properties of soils

A. COHESIONLESS SOILS		
	Gravels	*Sands*
Relative density	2.5 –2.8	2.6–2.7
Bulk density (t/m^3)	1.45–2.3	1.4–2.15
Dry density (t/m^3)	1.4 –2.1	1.35–1.9
Porosity (%)	20–50	23–35
Shear strength (kPa)	200–600	100–400
Angle of friction (deg)	35–45	32–42
B. COHESIVE SOILS		
	Silts	*Clays*
Relative density	2.64–2.66	2.55–2.75
Bulk density (t/m^3)	1.82–2.15	1.5–2.15
Dry density (t/m^3)	1.45–1.95	1.2–1.75
Void ratio	0.35–0.85	0.42–0.96
Liquid limit (%)	24–35	Over 25
Plastic limit (%)	14–25	Over 20
Coefficient of consolidation (m^2/yr)	12.2	5–20
Effective cohesion (kPa)	75	20–200
Effective angle of friction (deg)	32–36	
C. ORGANIC SOILS AND FILL		
	Peat	*Coarse discard*
Moisture content (%)	650–1100	6–14
Relative density	1.3 –1.7	1.8–2.7
Bulk density (t/m^3)	0.91–1.05	1.2–2.4
Dry density (t/m^3)	0.07–0.11	1.05–2.0
Void ratio	12.7–14.9	0.35–over 1
Liquid limit (%)		23–45
Plastic limit (%)		Non-plastic–35
Effective angle of friction (deg)	5	28–40
Effective cohesion (kPa)	20	20–50

1.2 Specific Gravity

The densities of substances making up rocks, or of a rock itself, are sometimes expressed in terms of the density ρ_w of liquid water. The *specific gravity* G of a substance is defined by

$$G = \frac{\rho}{\rho_w}, \tag{1.2}$$

where ρ is the density of the substance. Since G is the ratio of two densities, the density units cancel, so that G has no units. (This requires that both densities in Eq.(1.2) must be expressed in the same units, either both kg/m^3 or g/cm^3; it would lead to meaningless confusion if one density is in kg/m^3 and the other g/cm^3.)

For the density of water it is common to use $\rho_w = 1.00$ g/cm^3. The density of water varies slightly with temperature (as does the density of other substances), but this variation can often (not always) be ignored. In the present work, the density of water will be taken as 1000 kg/m^3 exactly for the purpose of calculating specific gravity.

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EXAMPLE 1
A block of rock with edge lengths 85.5 cm, 79.0 cm, 43.8 cm has a mass of 953 kg. Find the specific gravity of the rock.

Some of the data are in SI base units (the mass), the rest are in cgs units (the edge lengths). Calculations should be done either with all base units or all cgs units. In engineering, the base units are more commonly used. (But not always: sometimes SI base units and cgs units are mixed!) Using all SI base units means that the edge lengths must be converted to meters. But this is easy since 1 m = 100 cm. By "block" of rock is implied a rectangular block whose volume is the product of the edge lengths. Therefore,

$$V = (0.855 \text{ m})(0.790 \text{ m})(0.438 \text{ m}),$$
$$V = 0.2958 \text{ m}^3.$$

By Eq.(1.1), the density is

$$\rho = \frac{M}{V},$$

$$\rho = \frac{953 \text{ kg}}{0.2958 \text{ m}^3},$$

$$\rho = 3222 \text{ kg/m}^3.$$

Now use Eq.(1.2) to find the specific gravity G. Since SI base units are being used here, the density of water ρ_w must be entered in these units. Therefore,

$$G = \frac{\rho}{\rho_w},$$

$$G = \frac{3222 \text{ kg/m}^3}{1000 \text{ kg/m}^3},$$
$$G = 3.22.$$

Since the data has 3 significant figures (sig fig), the final result can be given to no more than 3 sig fig, although 1 extra sig fig is carried within the calculation to guard against round-off error. As mentioned previously, the density of water is considered to be exact.

****

1.3 Unit Weight

The weight W of an object is the gravitational force exerted on it by the rest of the planet Earth. Dividing the weight W of an object by its volume V yields the *unit weight* γ of the object or of the material of which the object is made; that is,

$$\gamma = \frac{W}{V}. \tag{1.3}$$

The SI base unit of weight is the newton (N). Since the base unit of volume is m^3, the SI base unit of unit weight is N/m^3. (Note the two uses of the word *unit* in the last sentence.) The cgs unit of weight, the dyne, will not be used in this book; therefore, cgs units of unit weight will not be encountered in the present work.

Looking back at Eq.(1.1), it can be seen that the unit weight is defined very like the bulk density, except that the weight W replaces the mass M. (For this reason, unit weight is also known as *weight density.*) There is a relation between weight and mass. From physics,

$$W = Mg, \tag{1.4}$$

where g is the acceleration due to gravity (often called simply *gravity*). Hence,

$$\gamma = Mg/V,$$
$$\gamma = (M/V)g,$$
$$\gamma = \rho g. \tag{1.5}$$

Equation (1.5) can be used to calculate unit weight from density, and vice versa. The numerical value of g to be used is

$$g = 9.8 \text{ m/s}^2.$$

This value is often adopted as the value of gravity averaged over the surface of the Earth. For the purpose of evaluating the significant figures in any calculation, this value for g shall be considered exact.

Note that Eq.(1.2) for specific gravity can be written in terms of unit weight:

$$G = \rho/\rho_w,$$

$$G = \rho g/\rho_w g,$$

$$G = \gamma/\gamma_w. \tag{1.6}$$

The unit weight of water is, by Eq.(1.5),

$$\gamma_w = \rho_w g,$$

$$\gamma_w = (1000 \text{ kg/m}^3)(9.8 \text{ m/s}^2),$$

$$\gamma_w = 9.8 \text{ kN/m}^3.$$

The SI prefix k stands for 1 X 10^3.

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EXAMPLE 2
Calculate the density in g/cm^3 of a rock with unit weight 27.6 kN/m^3.

As noted just above, the SI prefix k means a factor of 1000. By Eq.(1.5),

$$\gamma = \rho g,$$
$$27.6 \text{ X } 10^3 \text{ N/m}^3 = \rho(9.8 \text{ m/s}^2),$$
$$\rho = 2820 \text{ kg/m}^3,$$
$$\rho = 2.82 \text{ g/cm}^3.$$

The answer is given to 3 sig fig since the data is given to 3 sig fig (remember that the value $g = 9.8$ m/s^2 is considered to be of infinite precision). Also, the density conversion factor between kg/m^3 and g/cm^3 is used in the last step.

****

1.4 Porosity

Under a microscope, most types of rock are seen to contain small open spaces, called *pores*. These pores can originate in various ways. For example, many sedimentary rocks seem to be assembled from many small, solid particles, called *grains*. These grains are irregularly shaped. However, unlike a jigsaw puzzle in which the irregularly shaped pieces completely

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EXAMPLE 3

A 0.885-m^3 block of sandstone has a mass of 1752 kg. When the block is crushed just sufficiently to close all the pores, which are empty, the volume of the rock becomes 0.584 m^3. Find (*a*) the porosity of the sandstone and (*b*) the density of the grains. (Assume that the density of the grains is not changed in the crushing process.)

(*a*) The original block has a volume $V = 0.885\ \mathrm{m}^3$. The volume of the crushed rock must equal the volume of all the grains in the original block, since the crushed rock has zero pore volume. That is, in the original block, $V_{\mathrm{grains}} = 0.584\ \mathrm{m}^3$. Therefore, the volume of the pores in the original block is, by Eq.(1.8),

$$V = V_{\mathrm{pores}} + V_{\mathrm{grains}},$$
$$0.885\ \mathrm{m}^3 = V_{\mathrm{pores}} + 0.584\ \mathrm{m}^3,$$
$$V_{\mathrm{pores}} = 0.301\ \mathrm{m}^3.$$

Now calculate the porosity by Eq.(1.7):

$$n = V_{\mathrm{pores}}/V,$$
$$n = (0.301\ \mathrm{m}^3)/(0.885\ \mathrm{m}^3),$$
$$n = 0.340\ (34.0\%).$$

(*b*) Since the pores are empty, the mass of the crushed rock is the same as that of the original block, 1752 kg. The volume of the crushed rock is 0.584 m^3. But the crushed rock is entirely grains, and therefore, by Eq.(1.9),

$$\rho_{\mathrm{g}} = M_{\mathrm{grains}}/V_{\mathrm{grains}},$$
$$\rho_{\mathrm{g}} = (1752\ \mathrm{kg})/(0.584\ \mathrm{m}^3),$$
$$\rho_{\mathrm{g}} = 3000\ \mathrm{kg/m}^3,$$
$$\rho_{\mathrm{g}} = 3.00\ \mathrm{g/cm}^3.$$

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1.5 Dry and Saturated Unit Weights

The pores of *in situ* rock (rock as found in the Earth, undisturbed by human activity) may be filled with gas or liquid. The densities of gases found in rocks are very much less than the densities of the grains or matrix of the rocks. This means that, as already mentioned, it is safe to ignore the contribution of the gas trapped in the pores to the total weight of a rock sample.

A similar statement cannot be made for liquids. The densities of the liquids commonly found in the pores of rocks, although less than the densities of the grains, are not very much

A similar relation holds between the mass densities. By Eq.(1.5), Eq.(1.17) becomes

$$\rho_{sat} g = \rho_{dry} g + n(\rho_L g),$$

$$\rho_{sat} = \rho_{dry} + n\rho_L. \tag{1.18}$$

Example 4 below describes how these relations can be used to determine the porosity of a rock sample by injecting it with mercury Hg. Liquid mercury is much denser than water: $G_{Hg} = 13.6$ compared with $G_w = 1$ for water. This implies that, even if the porosity of the rock sample is quite small, saturating the rock with mercury could change the unit weight significantly, making accurate laboratory measurements of the weights and their differences relatively easy. A disadvantage is that liquid mercury is a hazardous substance, mainly because of its vapor; great care must be exercised with its use.

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EXAMPLE 4

A test cylinder of rock has a diameter of 12.6 cm and a length of 14.0 cm. When dry its weight is 50.3 N. When saturated with mercury the weight of the sample is 62.8 N. The specific gravity of mercury is 13.6. Find the porosity of the rock.

$G_L = \frac{\rho_L}{\rho_W}$

The volume of the rock sample is

$$V = \pi D^2 L/4,$$

$$V = \pi(0.126 \text{ m})^2(0.140 \text{ m})/4,$$

$$V = 1.746 \text{ X } 10^{-3} \text{ m}^3.$$

Therefore, the dry and saturated unit weights are

$$\gamma_d = \gamma_{dry} = W_{dry}/V,$$

$$\gamma_{dry} = (50.3 \text{ N})/(1.746 \text{ X } 10^{-3} \text{ m}^3),$$

$$\gamma_{dry} = 28.81 \text{ kN/m}^3;$$

$$\gamma_{sat} = W_{sat}/V,$$

$$\gamma_{sat} = (62.8 \text{ N})/(1.746 \text{ X } 10^{-3} \text{ m}^3),$$

$$\gamma_{sat} = 35.97 \text{ kN/m}^3.$$

The unit weight of the liquid mercury γ_L follows from Eq.(1.6):

$$\gamma_L = G_L \gamma_w,$$

$$\gamma_L = (13.6)(9.8 \text{ kN/m}^3),$$

$$\gamma_L = 133.3 \text{ kN/m}^3.$$

Note that the unit weight of the mercury is greater than the unit weight of the rock, whether dry or saturated. Now use Eq.(1.17) to solve for the porosity n. Note that the units of unit weight cancel, so that

$$\gamma_{sat} = \gamma_{dry} + n\gamma_L,$$

$$35.97 \text{ kN/m}^3 = 28.81 \text{ kN/m}^3 + n(133.3 \text{ kN/m}^3),$$

$$n = 0.0537 \text{ (5.37\%)}.$$

****

porosity, they are

$$V_{\text{matrix}} = (1 - n_0)(H_0 w L),$$
$$V_{\text{matrix}} = (1 - n)(H w L).$$

Setting these expressions equal gives

$$(1 - n_0)(H_0 w L) = (1 - n)(H w L),$$
$$(1 - n_0)H_0 = (1 - n)H,$$
$$(1 - n_0)H_0 = (1 - n)(H_0 - \Delta H),$$
$$\Delta H = H_0[\frac{n_0 - n}{1 - n}]. \quad (1.19)$$

Greatest settlement is when $n = 0$.

$\boxed{\Delta H_{max} = H_0 n_0.}$

Equation(1.19) applies only to a trench with a rectangular cross section, since the volume of the material was presumed to be given by the product of the three edge lengths.

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EXAMPLE 5

$n_0 = 47\%$

A layer of clay with a porosity of 47.0% and saturated with water is deposited into a rectangular trench 260 m long and 17.5 m wide to a depth of 2.72 m. Later, it is found that the clay has settled by 15.0 cm. Find the volume of water squeezed out of the clay.

0.15 m.

The subsidence and the original height must be expressed in the same units, so that these units will cancel. Choosing meters, and remembering to express the porosity in decimal form, Eq.(1.19) becomes, after substitution of the data,

$$0.150 = 2.72[\frac{0.470 - n}{1 - n}],$$
$$\boxed{n = 0.4391.}$$

Since the clay was saturated, the volume V_w of water squeezed out equals the loss of pore space in the clay due to the compaction. Therefore,

$n_0 = \frac{V_{w0}}{V_0}$ $n = \frac{V_w}{V}$

$$V_w = n_0(H_0 w L) - n(H w L),$$
$$V_w = (n_0 H_0 - n H) w L.$$

$\Delta V_w = n_0 V_0 - n V$

$\Delta V_w = n_0 H_0 w L - n H w L$

$\boxed{\Delta V_w = (n_0 H_0 - n H) w L.}$

Now H = 2.72 m - 0.15 m = 2.57 m, so that

$$V_w = [(0.470)(2.72 \text{ m}) - (0.4391)(2.57 \text{ m})](17.5 \text{ m})(260 \text{ m}),$$
$$V_w = 682 \text{ m}^3.$$

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