

# 2 Physical Properties of Soils

## 2.2 Origin of Soils

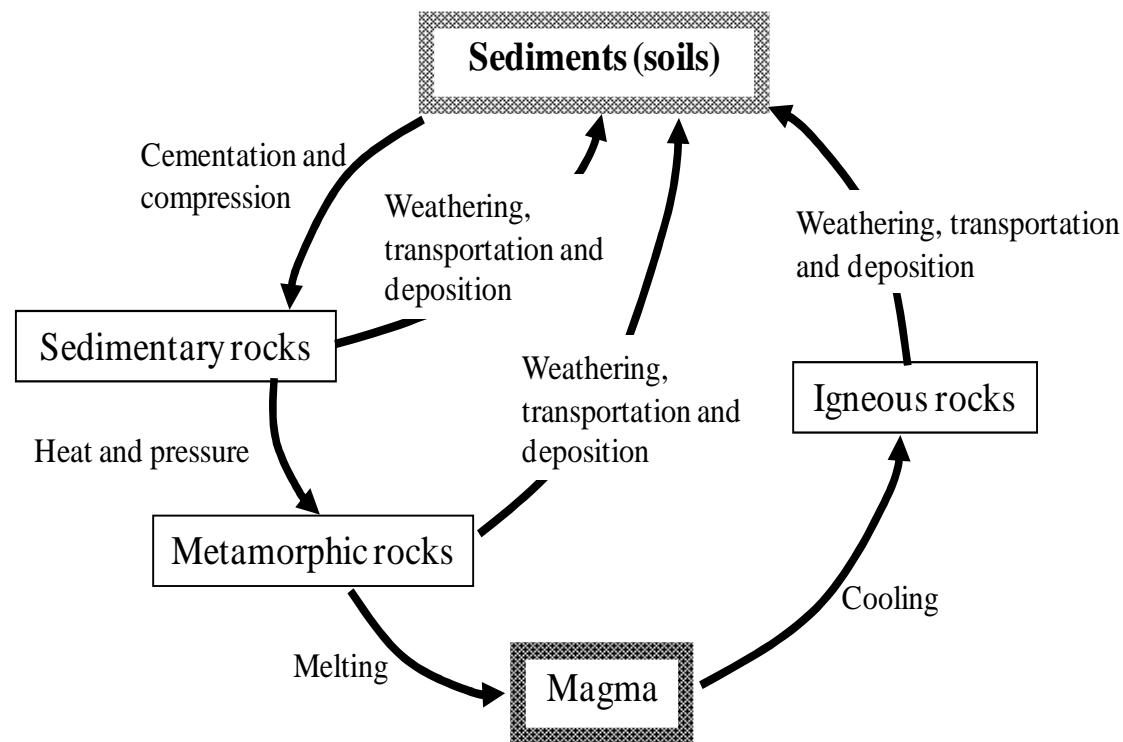


Fig. 2.1 Rock cycle

## 2.3

## Soil Particle Shapes

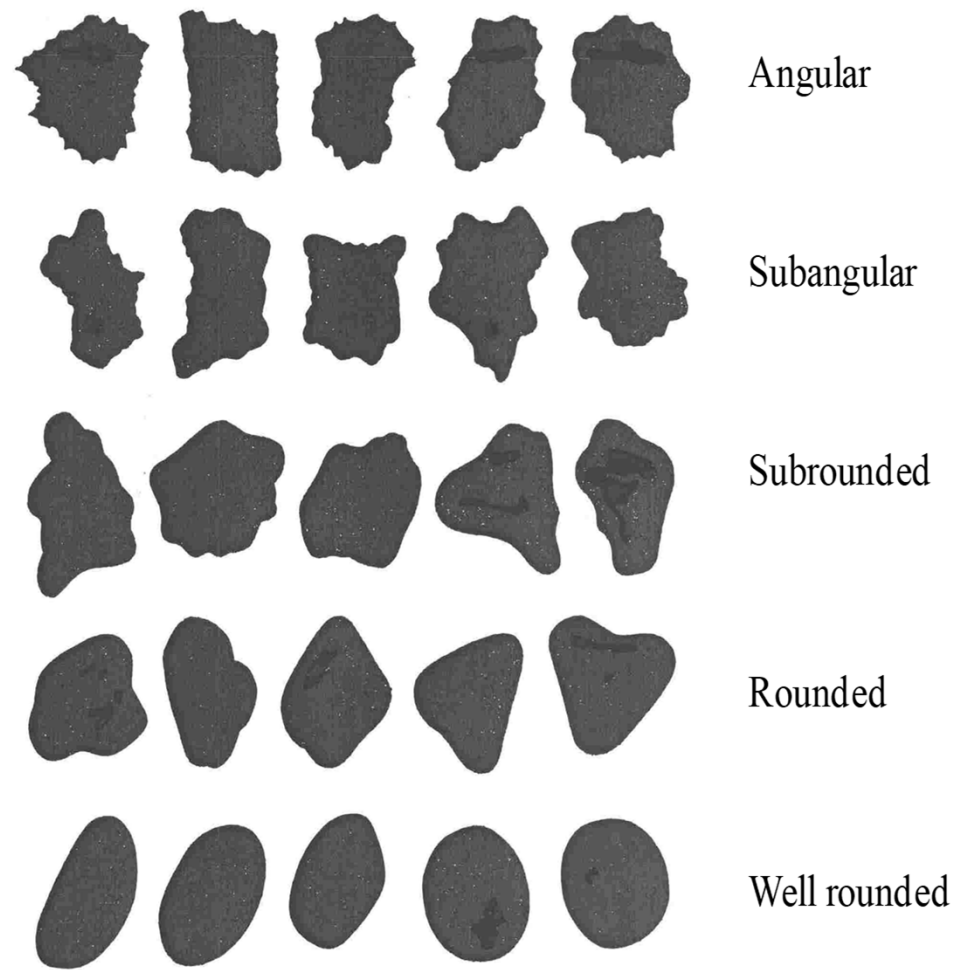


Fig. 2.2 Soil's angularity (Müller 1967)

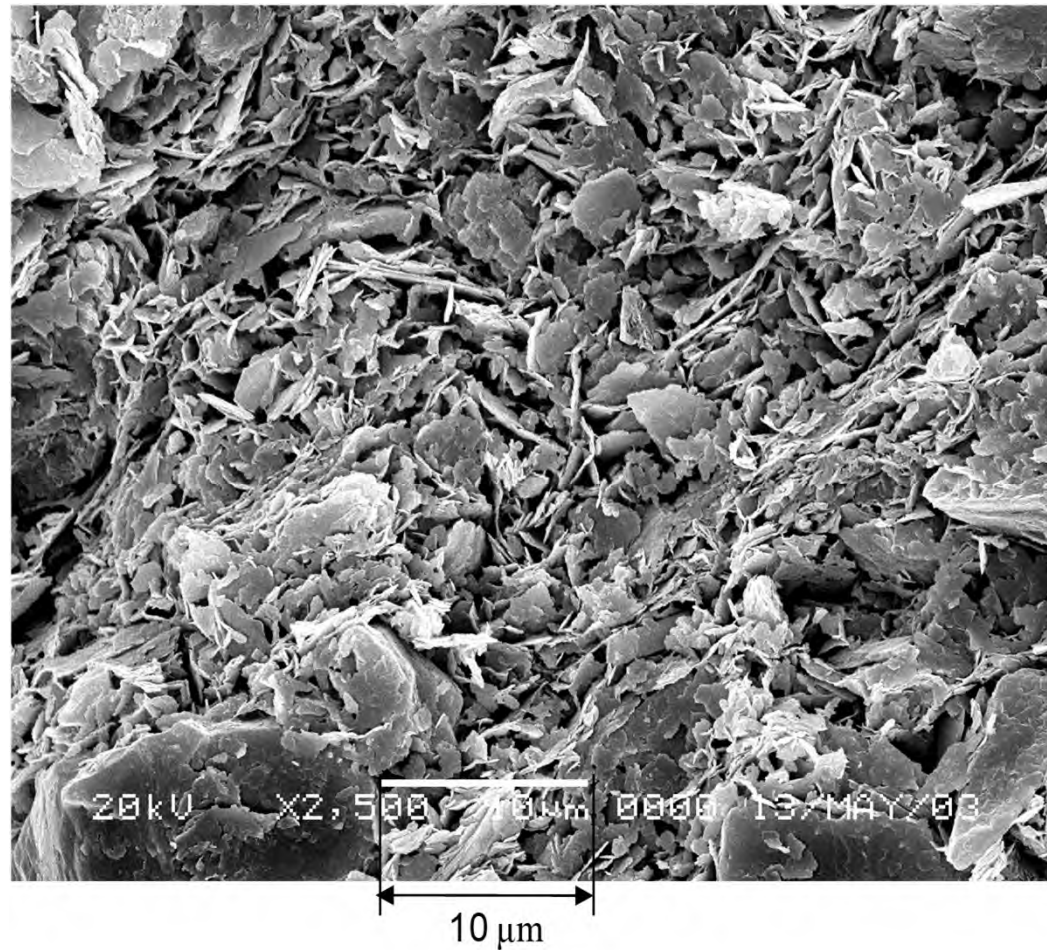


Fig. 2.3 Scanned Electron Microscope (SEM) picture of clay particle assembly (Hai-Phong (Vietnam) clay: 50 % Kaolinite and 50 % Illite) (**Watabe et al. 2004**)

## 2.4 Definitions of Terms with Three Phase Diagram

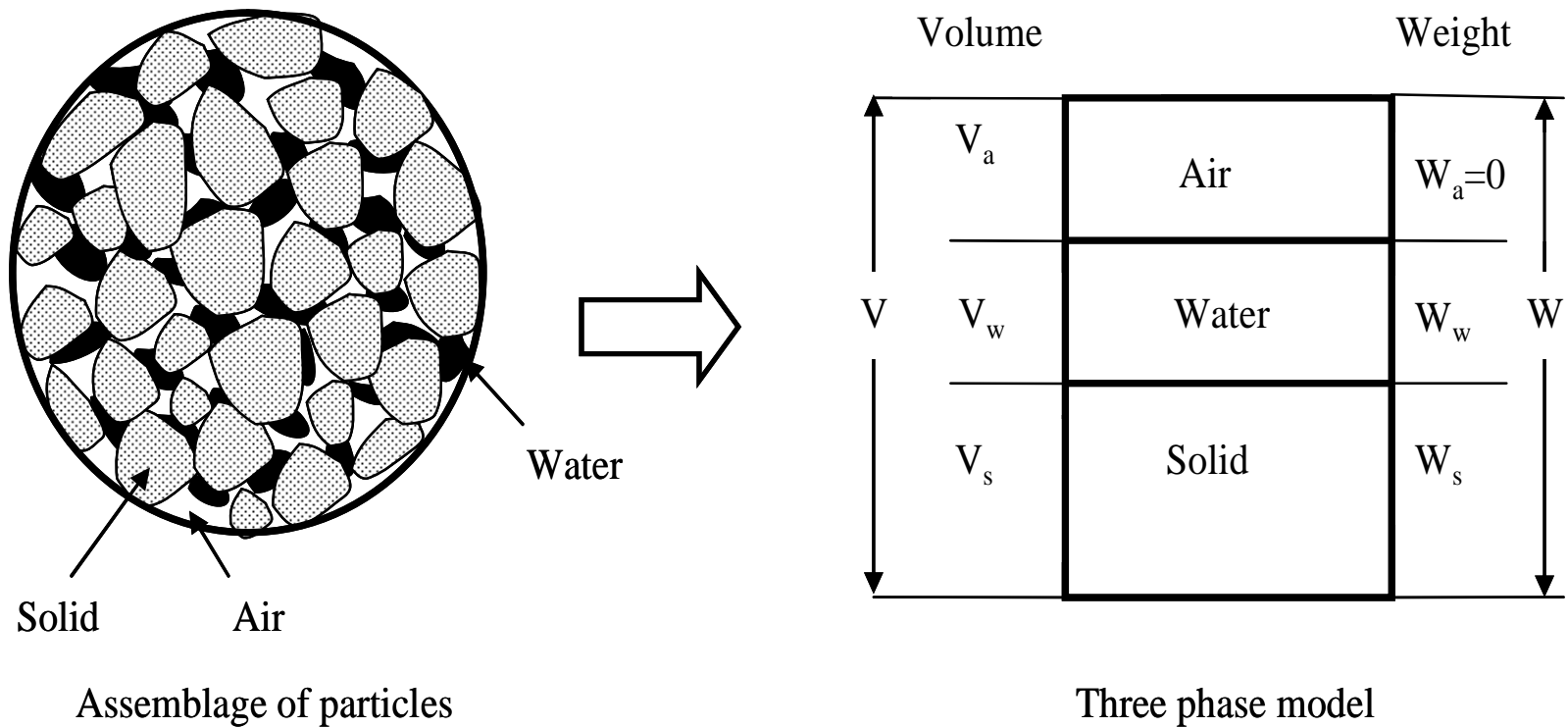


Fig. 2.4 Three phase diagram of soil

**Porosity:** 
$$n = \frac{\text{volume of void}}{\text{total volume}} = \frac{V_v}{V} = \frac{V_a + V_w}{V} \quad (2.1)$$

**Void ratio:** 
$$e = \frac{\text{volume of void}}{\text{volume of solid}} = \frac{V_v}{V_s} \quad (2.2)$$

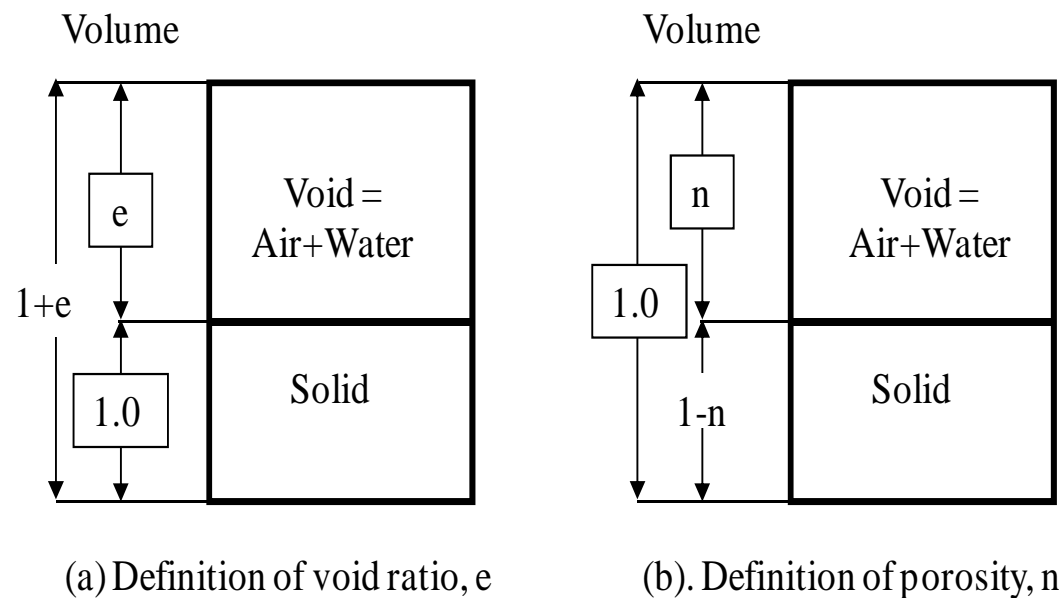


Fig. 2.5 Relationship between porosity,  $n$  and void ratio,  $e$

$$n = \frac{e}{1 + e} \quad \text{or} \quad e = \frac{n}{1 - n} \quad (2.3)$$

**Water content:**  $w = \frac{\text{weight of water}}{\text{weight of solid}} = \frac{W_w}{W_s} \quad (\times 100 \%) \quad (2.4)$

**Degree of saturation:**

$$S = \frac{\text{volume of water}}{\text{volume of void}} = \frac{V_w}{V_v} \quad (\times 100 \%) \quad (2.5)$$

**Specific gravity:**

$$G_s = \frac{\text{unit weight of solid}}{\text{unit weight of water}} = \frac{W_s / V_s}{\gamma_w} \quad (2.6)$$

**Total unit weight:**

$$\gamma_t = \frac{\text{total weight}}{\text{total volume}} = \frac{W}{V} = \frac{W_s + W_w}{V_s + V_w + V_a} \quad (2.7)$$

**Dry unit weight:**  $\gamma_d = \frac{\text{weight of solid}}{\text{total volume}} = \frac{W_s}{V}$  (2.8)

$$\gamma_t = \frac{(1 + w)G_s}{1 + e} \gamma_w = \frac{G_s + Se}{1 + e} \gamma_w \quad (2.9)$$

$$\gamma_t = (1 + w) \frac{G_s \gamma_w}{1 + e} = (1 + w) \gamma_d \quad \text{or} \quad \gamma_d = \frac{G_s \gamma_w}{1 + e} = \frac{\gamma_t}{1 + w} \quad (2.10)$$

**submerged unit weight or buoyant unit weight**

$$\gamma' = \gamma_t - \gamma_w = \frac{G_s + Se}{1 + e} \gamma_w - \gamma_w = \frac{G_s - 1 - e(1 - S)}{1 + e} \gamma_w$$

**(for partially saturated)**

**(2.11)**

$$\gamma' = \gamma_t - \gamma_w = \frac{G_s + e}{1 + e} \gamma_w - \gamma_w = \frac{G_s - 1}{1 + e} \gamma_w$$

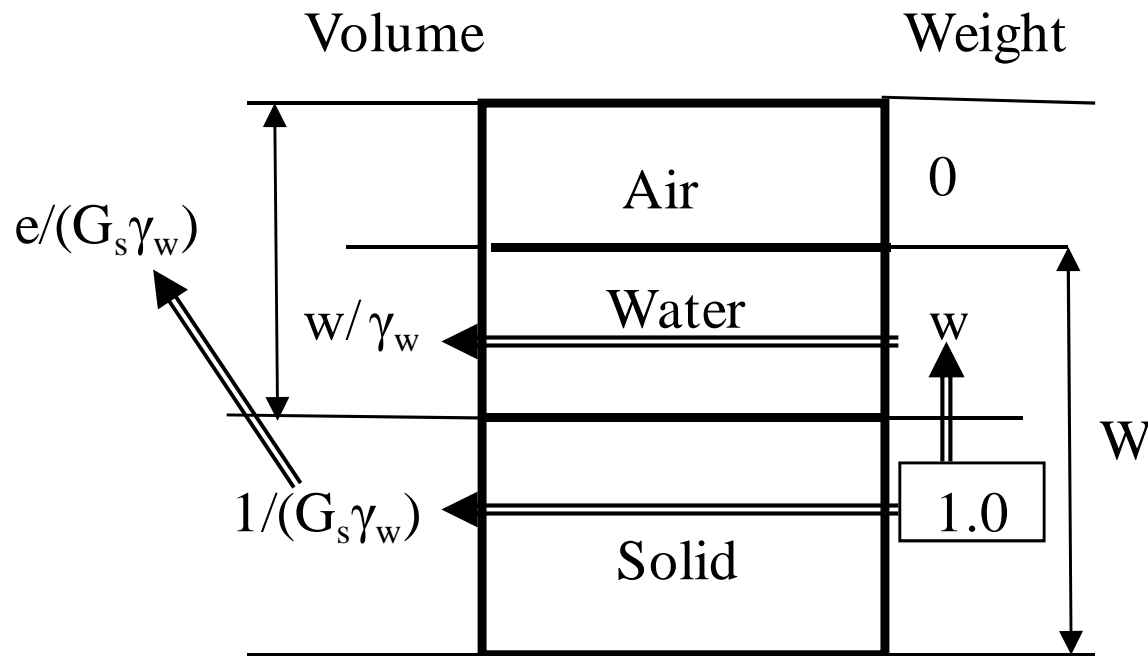
**(for fully saturated)**

**(2.12)**

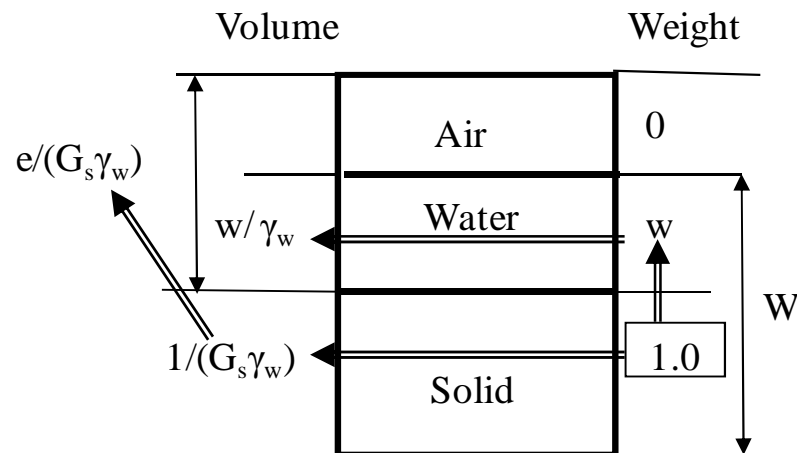


### Exercise 2.1

Using three phase diagram for a general soil, derive a formula to determine  $\gamma_t$  from known values of  $S$ ,  $e$ ,  $w$ , and  $G_s$ .



first assume that  $W_s=1$ , then  $W_w=w$



$$G_s = \frac{W_s}{V_s} / \gamma_w, \quad \text{thus } V_s = \frac{W_s}{G_s \gamma_w} = \frac{1}{G_s \gamma_w}$$

$$\gamma_w = \frac{W_w}{V_w}, \quad \text{thus } V_w = \frac{W_w}{\gamma_w} = \frac{w}{\gamma_w}$$

$$S = \frac{V_w}{V_a + V_w}, \quad \text{thus } V_a = \frac{(1-S)V_w}{S} = \frac{(1-S)w}{S\gamma_w}$$

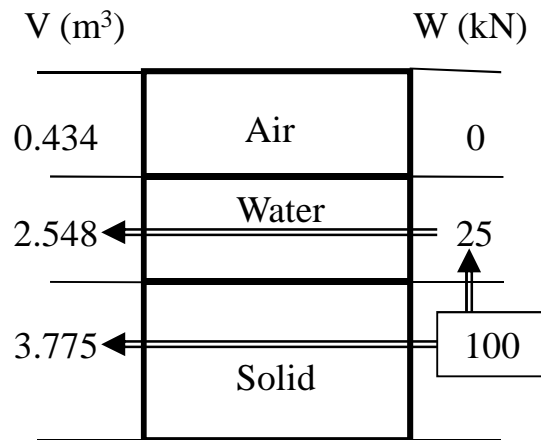
$$e = \frac{V_a + V_w}{V_s} = \frac{V_a + V_w}{1/G_s \gamma_w}, \quad \text{thus } V_a + V_w = \frac{e}{G_s \gamma_w}$$

$$S = \frac{V_w}{V_a + V_w} = \frac{w/\gamma_w}{e/G_s \gamma_w} = \frac{wG_s}{e}, \quad \text{then } Se = wG_s$$

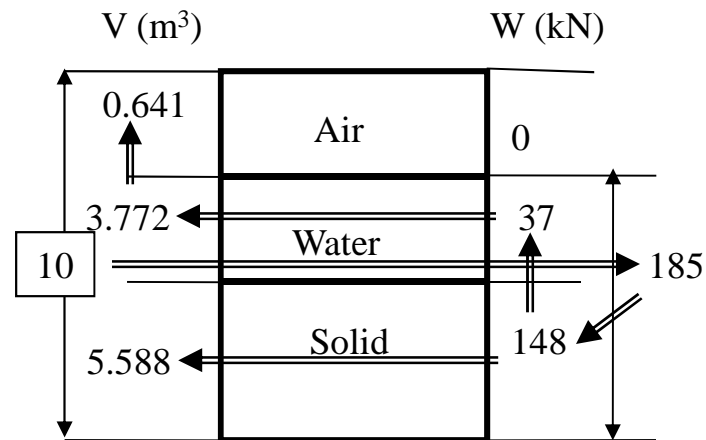
$$\gamma_t = \frac{W_s + W_w}{V_a + V_w + V_s} = \frac{1 + w}{e/G_s \gamma_w + 1/G_s \gamma_w} = \frac{(1 + w)G_s}{1 + e} \gamma_w = \frac{G_s + wG_s}{1 + e} \gamma_w = \frac{G_s + Se}{1 + e} \gamma_w$$

## Exercise 2.2

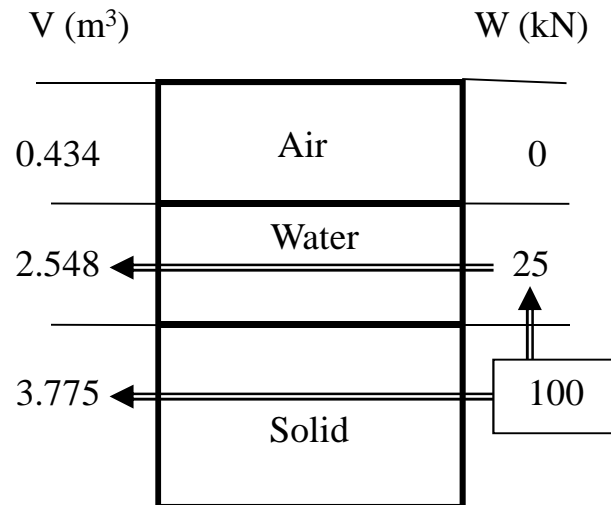
For a given soil,  $w=25\%$  and  $\gamma_t = 18.5 \text{ kN/m}^3$  are measured. Determine void ratio  $e$  and degree of saturation  $S$ . Assume that  $G_s$  is 2.70.



Solution (a)



Solution (b)



Solution (a)

### Solution (a):

First assume  $W_s = 100$  kN as seen in Fig. 2.6(a). Then  $W_w = 100 \times 0.25 = 25$  kN.

Calculate  $V_s = W_s / G_s \gamma_w = 100 / (2.7 \times 9.81) = 3.775$  m<sup>3</sup>.

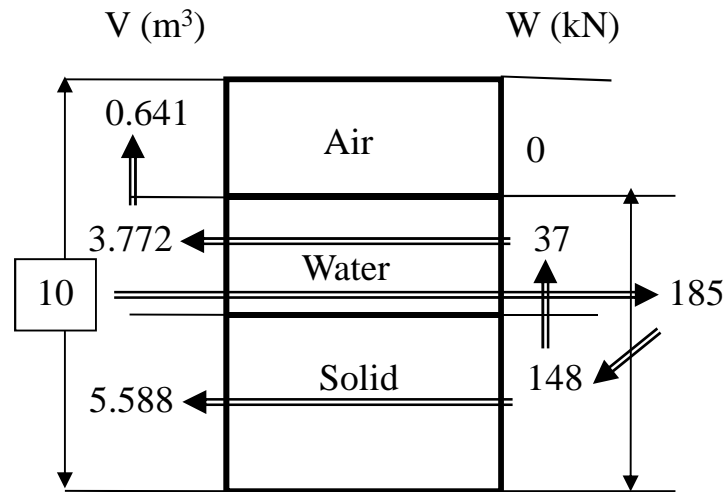
Calculate  $V_w = W_w / \gamma_w = 25 / 9.81 = 2.548$  m<sup>3</sup>.

Since  $\gamma_t = 18.5$  kN/m<sup>3</sup> =  $(W_s + W_a) / (V_s + V_w + V_a) = (100 + 25) / (3.775 + 2.548 + V_a)$ , thus,  $V_a = 0.434$  m<sup>3</sup>.

Now, all components in the three phase are obtained as shown in Fig. 2.6(a) and,

$e = (V_w + V_a) / V_s = (2.548 + 0.434) / 3.775 = \mathbf{0.790} \leftarrow$

$S = V_w / (V_w + V_a) = 2.548 / (2.548 + 0.434) = 0.854 = \mathbf{85.4 \%} \leftarrow$



Solution (b)

### Solution (b):

First assume  $V=10 \text{ m}^3$  as seen in Fig. 2.6(b).

From  $W_s + W_w = W_s + wW_s = (1+w)W_s = V\gamma_t = 10 \times 18.5 = 185 \text{ kN}$ ,

$W_s = 185 / (1 + 0.25) = 148 \text{ kN}$ , and  $W_w = 185 - 148 = 37 \text{ kN}$ .

Using  $G_s$  as a bridge value,  $V_s = W_s / G_s \gamma_w = 148 / (2.7 \times 9.81) = 5.588 \text{ m}^3$ .

Using  $\gamma_w$  as a bridge value,  $V_w = W_w / \gamma_w = 37 / 9.81 = 3.772 \text{ m}^3$ .

Thus  $V_a = V - (V_s + V_w) = 10 - (5.588 + 3.772) = 0.641 \text{ m}^3$ .

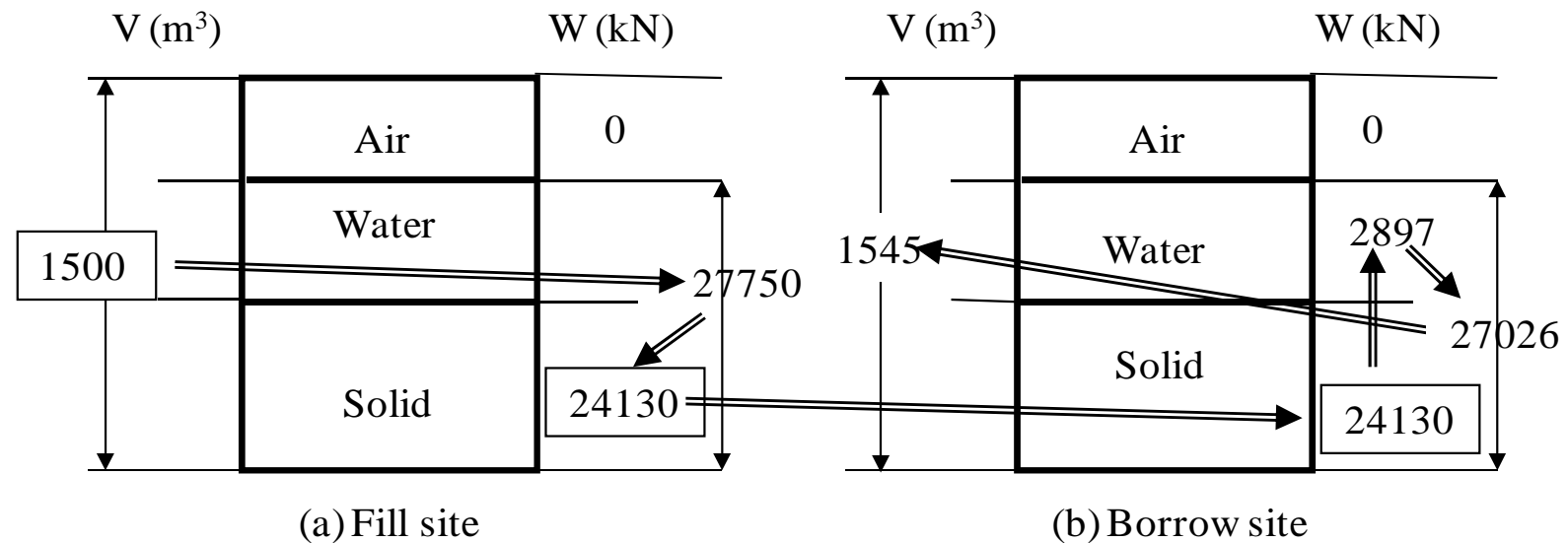
Now, all components in the three phase are obtained as shown in Fig. 2.6(b) and,

$$e = (V_w + V_a) / V_s = (3.772 + 0.641) / 5.588 = \mathbf{0.789}. \leftarrow$$

$$S = V_w / (V_w + V_a) = 3.772 / (3.772 + 0.641) = 0.855 = \mathbf{85.5 \%}. \leftarrow$$

### Exercise 2.3

In a fill section of a construction site,  $1500 \text{ m}^3$  of moist compacted soils is required. The design water content of the fill is 15 % and the design density of the compacted soil is  $18.5 \text{ kN/m}^3$ . Necessary soil is brought from a borrow site with a soil having 12 % natural water content,  $17.5 \text{ kN/m}^3$  wet density, and  $G_s=2.65$ . How much (in cubic meters) of the borrow material is required to fill the construction fill section? And how heavy is it?



### Solution:

Draw three phase diagrams of the fill site and the borrow site in Fig. 2.8(a) and 2.8(b), respectively.

First for the fill site in Fig. 2.8(a),  $V=1500 \text{ m}^3$  so that  $W_s+W_w = V\gamma_t = 1500 \times 18.5 = 27750 \text{ kN}$ .

$W_s+W_w=(1+w)W_s=27750 \text{ kN}$ , so that  $W_s = 27750/(1+0.15) = 24130 \text{ kN}$ .

This much solid weight of the soil is required at the fill site.

At the borrow site, the same solid weight  $24130 \text{ kN}$  is needed as shown in Fig. 2.8(b).

Thus  $W_w=wW_s=0.12 \times 24130 = 2897 \text{ kN}$ , and  $W_s+W_w=24130+2897=27026 \text{ kN}$ . ←

Since  $\gamma_t = (W_s+W_w)/V=17.5 \text{ kN/m}^3$ ,  $V = 27026/17.5 = 1545 \text{ m}^3$ . ←

Thus,  $1545 \text{ m}^3$  of the borrow material is needed for the project carrying a total weight of  $27026 \text{ kN}$ .

## 2.5 Particle Size and Gradation

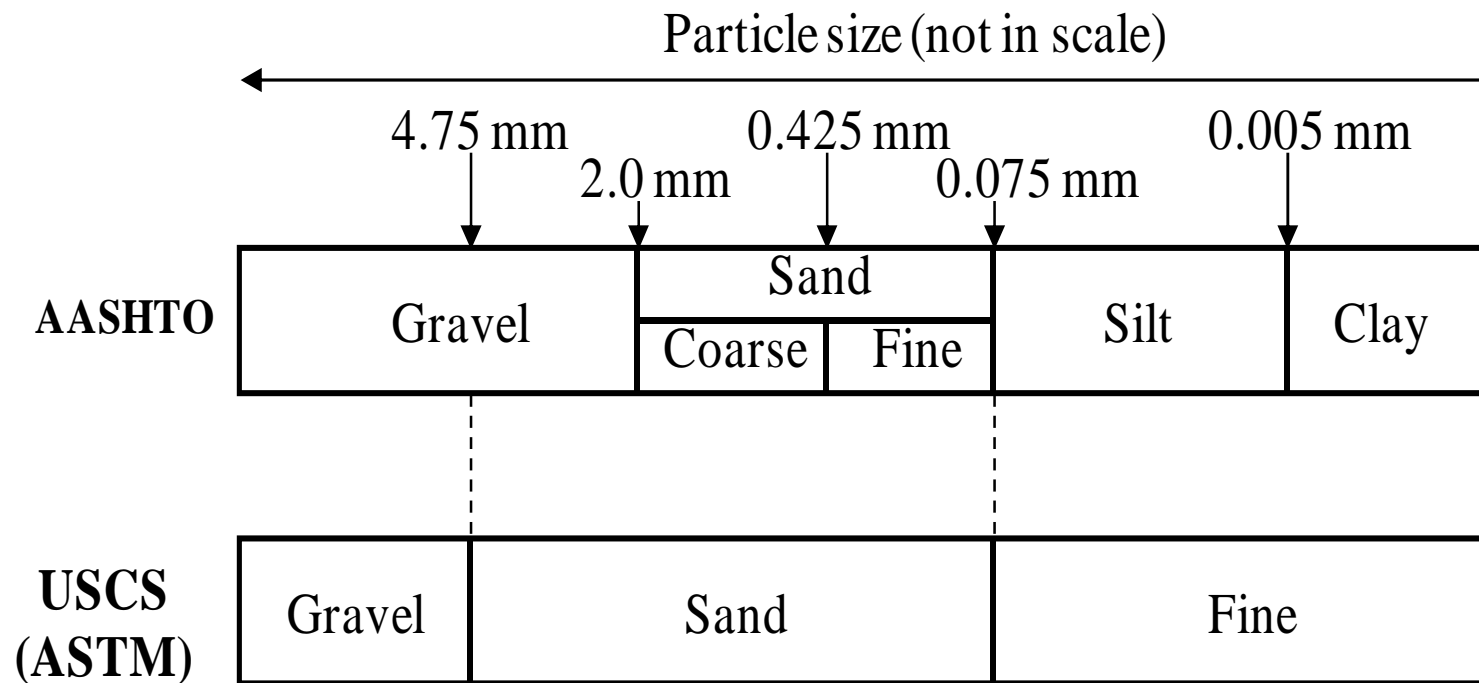


Fig. 2.9 Soil's names with grain sizes

Note: British soil classification (**BS8004, 1986**), **2  $\mu$ m** is used as the boundary between **silt and clay**

Table 2.1 U.S. Standard Sieve Numbers and openings

U.S. Standard Sieve No.	Opening in mm
4	4.75
10	2.00
20	0.85
40	0.425
60	0.25
100	0.15
140	0.106
200	0.075



Table 2.2 Example computation of sieve analysis

	A	B	C	D	E	F
i	U.S. Standard Sieve No	Opening mm	Weight Retained gf	% Weight Retained	% Cumulative Retained	% Finer
1	4	4.75	0	0.0	0.0	100
2	10	2.00	16.8	3.1	3.1	96.9
3	20	0.85	37.8	7.0	10.1	89.9
4	40	0.425	45.9	8.5	18.5	81.5
5	60	0.25	44.4	8.2	26.7	73.3
6	100	0.15	52.5	9.7	36.4	63.6
7	140	0.106	50.7	9.3	45.7	54.3
8	200	0.075	39.0	7.2	52.9	47.1
9	Pan		255.6	47.1	100	0
10		summation	542.7	100		

Column  $D(i) = C(i) / C(10) \times 100$

Column  $E(1) = D(1)$  and  $E(i) = E(i-1) + D(i)$

Column  $F(i) = 100 - E(i)$

## Hydrometer analysis

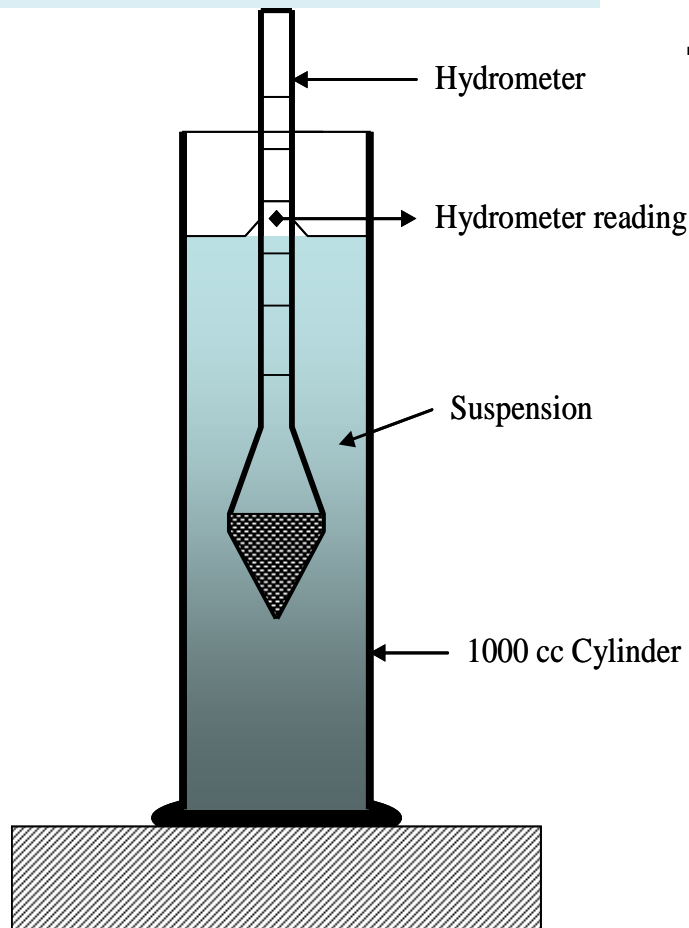


Fig. 2.10 Hydrometer test setup

Table 2.3 Example of hydrometer test result

A	B	C
Particle Dia. D, mm	% finer	Modified % finer
0.066	84.5	45.7
0.045	74.3	40.2
0.036	68.3	37.0
0.025	58.2	31.5
0.015	48.4	26.2
0.011	42.3	22.9
0.007	34.6	18.7
0.005	28.1	15.2
0.004	24.3	13.2
0.003	20.1	10.9
0.0018	16.2	8.8
0.0012	12.3	6.7

$$\text{Column C} = \text{Column B} \times F_{200 (\text{Curve 1})} / F_{200 (\text{Curve 2})}$$

## Combined grain size analysis

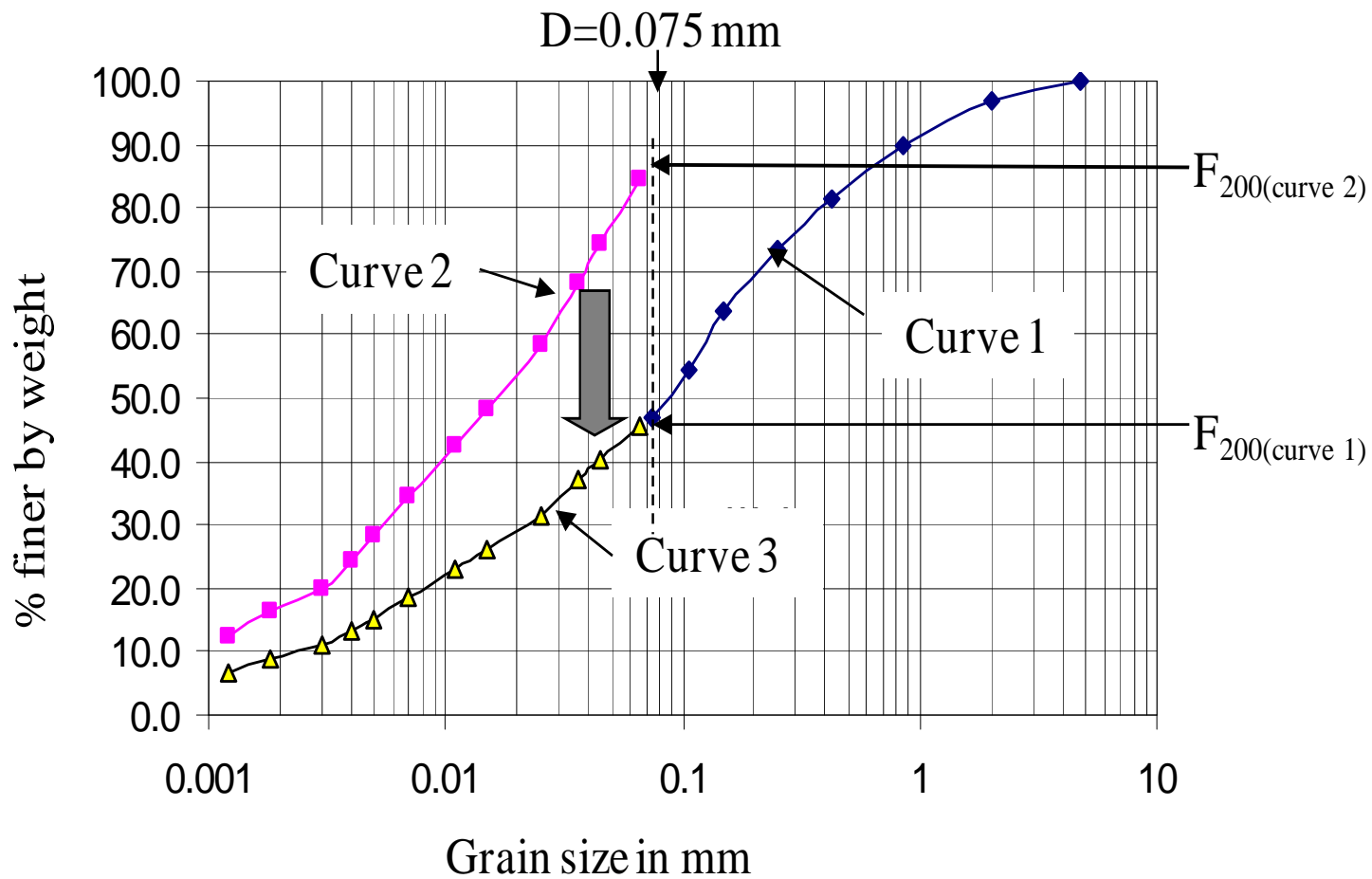


Fig. 2.11 Combined grain size analysis

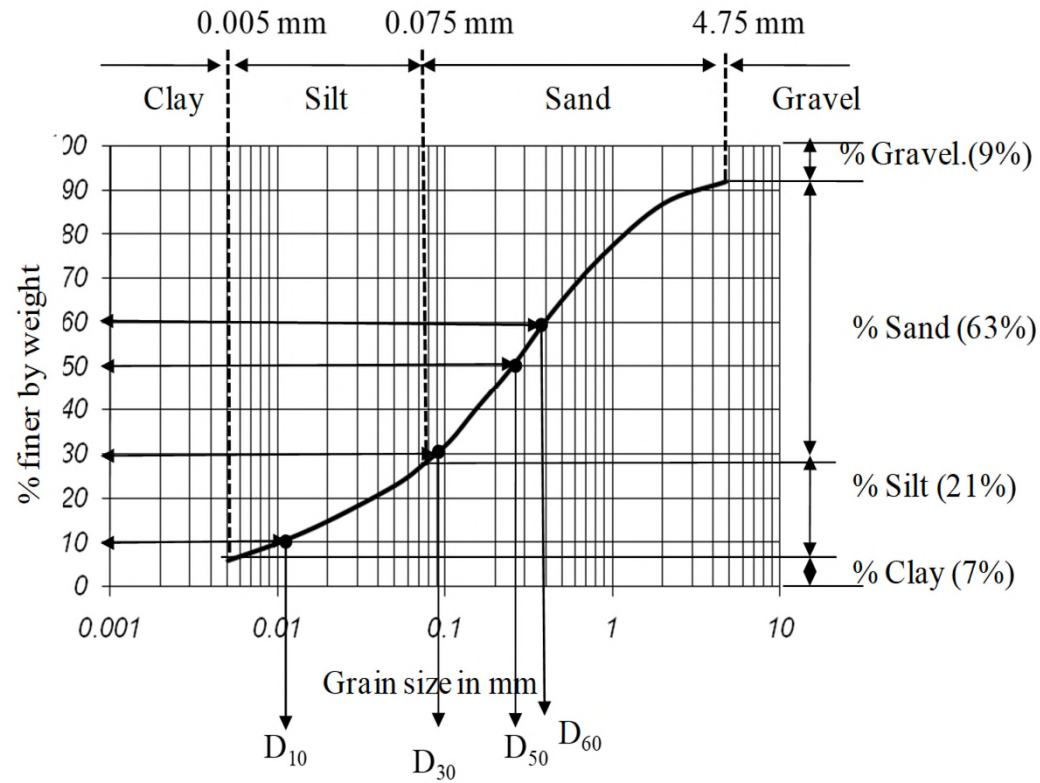


Fig. 2.12 Grain size distribution curve

**D<sub>50</sub>: Mean grain size**

**D<sub>10</sub>: Effective grain size**

**Coefficient of uniformity**  $C_u = D_{60} / D_{10}$  (2.19)

**Coefficient of gradation**  $C_c = \frac{D_{30} / D_{10}}{D_{60} / D_{30}} = \frac{(D_{30})^2}{D_{60} D_{10}}$  (2.20)

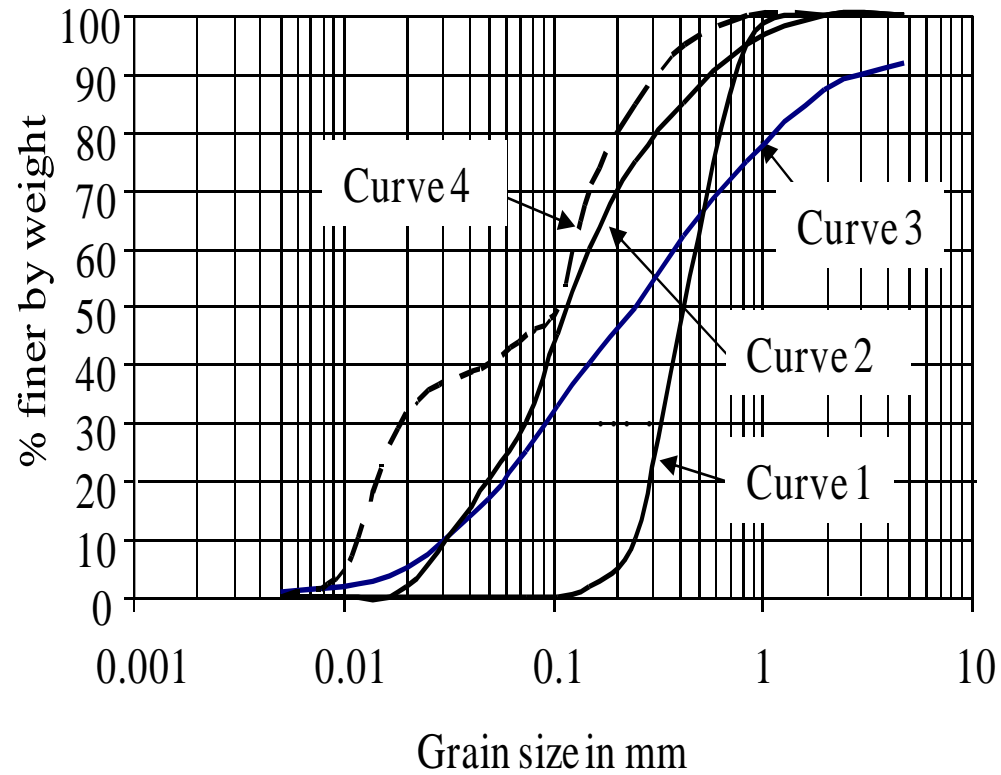


Fig. 2.13 Various grain size distribution curves

**uniformly graded (or poorly graded) soil**

**well graded soil**

**gap graded soils**