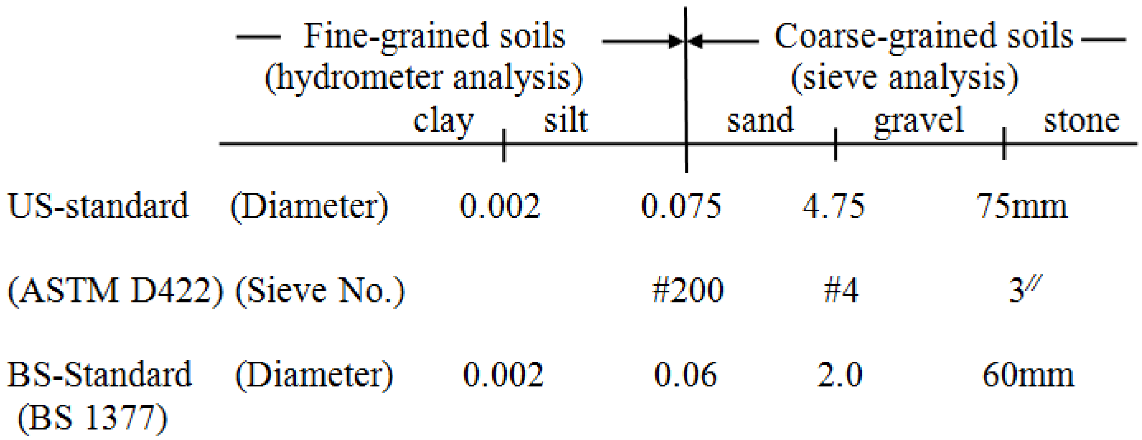
Chapter 5: Classification of Soil

5.1 Mechanical Analysis (Particle Size Analysis) of Soils

Mechanical analysis is the determination of the size range of particles present in a soil, expressed as a percentage of the total dry weight. Two methods generally are used to find the particle-size distribution of soil: (1) sieve analysis-for coarse-grained soils, and (2) hydrometer analysis-for fine-grained soils.



Sieve analysis

Sieve analysis consists of shaking the soil sample through a set of sieves that have progressively smaller openings. U.S. standard sieve numbers and the sizes of openings are given in Table (5.1).

Table (5.1) U.S. standard Sieve sizes

Sieve no.	Opening (mm)	Sieve no.	Opening (mm)
4	4.75	35	0.500
5	4.00	40	0.425
6	3.35	50	0.355
7	2.80	60	0.250
8	2.36	70	0.212
10	2.00	80	0.180
12	1.70	100	0.150
14	1.40	120	0.125
16	1.18	140	0.106
18	1.00	170	0.090
20	0.850	200	0.075
25	0.710	270	0.053
30	0.600		

To conduct a sieve analysis, one must first oven dry the soil and then shaken a known weight of soil through a stack of sieves (Figure 5.1) with openings of decreasing size from top to bottom (a pan is placed below the stack). The smallest-size sieve that should be used is the US NO. 200 sieve. The soil retained on each sieve is weighted and the percentage of soil retained on each sieve is calculated. The results are plotted on a graph of percent of particles finer than a given sieve as the ordinate versus the logarithm of the particle sizes.

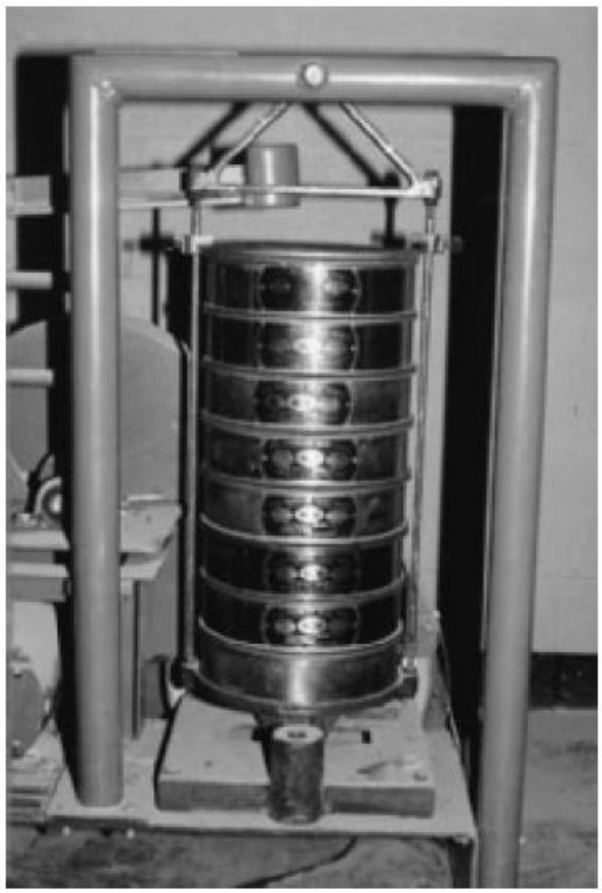


Figure (5.1) A set of sieves for test in the laboratory

Hydrometer Analysis

Hydrometer analysis is based on the principle of sedimentation of soil grains in water. When a soil specimen is dispersed in water, the particles settle at different velocities, depending on their shape, size, weight, and the viscosity of the water. For simplicity, it is assumed that all the soil particles are spheres and that the velocity of soil particles can be expressed by *Stokes' law*, according to which

$$v = \frac{\rho_s - \rho_w}{18\eta} D^2 \qquad (5.1)$$

where v = velosity

ρ_s = density of soil particles

ρ_w = density of water

η = viscosity of water

D = diameter of soil particles

Thus, from Eq. (5.1),

$$D = \sqrt{\frac{18\eta v}{\rho_s - \rho_w}} = \sqrt{\frac{18\eta}{\rho_s - \rho_w}} \sqrt{\frac{L}{t}} \qquad (5.2)$$

where $v = \frac{Distance}{Time} = \frac{L}{t}$

Note that

$$\rho_s = G_s \rho_w \qquad (5.3)$$

Thus, combining Eqs. (5.2) and (5.3) gives

$$D = \sqrt{\frac{18\eta}{(G_s - 1)\rho_w}} \sqrt{\frac{L}{t}} \qquad (5.4)$$

If the units of η are (g.sec)/cm^2, ρ_w is in g/cm^3, L is in cm, t is in min, and D is in mm, then

$$\frac{D(mm)}{10} = \sqrt{\frac{18\eta [\frac{\text{g.sec}}{cm^2}]}{(G_s - 1)\rho_w (\frac{\text{g}}{cm^3})}} \sqrt{\frac{L(cm)}{t(\text{min}) \times 60}}$$

or

$$D = \sqrt{\frac{30\eta}{(G_s - 1)\rho_w}} \sqrt{\frac{L}{t}}$$

Assume ρ_w to be approximately equal to 1 g/cm^3, so that

$$D(mm) = K \sqrt{\frac{L(cm)}{t(\text{min})}} \qquad (5.5)$$

where

$$K = \sqrt{\frac{30\eta}{(G_s - 1)}} \qquad (5.6)$$

Note that the value of K is a function of G_s and η, which are dependent on the temperature of the test. Table (5.2) gives the variation of K with the test temperature and the specific gravity of soil solids.

Table (5.2) values of *K* for use in equation for computing diameter of particle in hydrometer analysis

Temperature, °C	Specific Gravity of Soil Particles								
	2.45	2.50	2.55	2.60	2.65	2.70	2.75	2.80	2.85
16	0.01510	0.01505	0.01481	0.01457	0.01435	0.01414	0.01394	0.01374	0.01356
17	0.01511	0.01486	0.01462	0.01439	0.01417	0.01396	0.01376	0.01356	0.01338
18	0.01492	0.01467	0.01443	0.01421	0.01399	0.01378	0.01359	0.01339	0.01321
19	0.01474	0.01449	0.01425	0.01403	0.01382	0.01361	0.01342	0.1323	0.01305
20	0.01456	0.01431	0.01408	0.01386	0.01365	0.01344	0.01325	0.01307	0.01289
21	0.01438	0.01414	0.01391	0.01369	0.01348	0.01328	0.01309	0.01291	0.01273
22	0.01421	0.01397	0.01374	0.01353	0.01332	0.01312	0.01294	0.01276	0.01258
23	0.01404	0.01381	0.01358	0.01337	0.01317	0.01297	0.01279	0.01261	0.01243
24	0.01388	0.01365	0.01342	0.01321	0.01301	0.01282	0.01264	0.01246	0.01229
25	0.01372	0.01349	0.01327	0.01306	0.01286	0.01267	0.01249	0.01232	0.01215
26	0.01357	0.01334	0.01312	0.01291	0.01272	0.01253	0.01235	0.01218	0.01201
27	0.01342	0.01319	0.01297	0.01277	0.01258	0.01239	0.01221	0.01204	0.01188
28	0.01327	0.01304	0.01283	0.01264	0.01244	0.01255	0.01208	0.01191	0.01175
29	0.01312	0.01290	0.01269	0.01249	0.01230	0.01212	0.01195	0.01178	0.01162
30	0.01298	0.01276	0.01256	0.01236	0.01217	0.01199	0.01182	0.01165	0.01149

The percent finer, *N*, can be estimated from:

$$N = \frac{G}{G - G_l} \frac{\gamma_w}{W_s} (R - G_l) \times 100\% \tag{5.7}$$

where w_s = weight of solid sample

R = hydrometer reading in sedimentation jar

G_l = specific gravity of the liquid (water) in which soil particles are suspended

5.2 Particle-Size Distribution Curve

A particle-size distribution curve can be used to determine the following parameters for a given soil (Figure 5.2):

1. *Effective size* (D_{10}): This parameter is the diameter in the particle-size distribution curve corresponding to 10% finer. The effective size of a granular soil is a good measure to estimate the hydraulic conductivity and drainage through soil.
2. *Uniformity coefficient* (C_u): This parameter is defined as

$$C_u = \frac{D_{60}}{D_{10}} \tag{5.8}$$

where D_{60} = diameter corresponding to 60% finer.

3. Coefficient of gradation (Cc): This parameter is defined as

$$C_c = \frac{D_{30}^2}{D_{60} \times D_{10}} \tag{5.9}$$

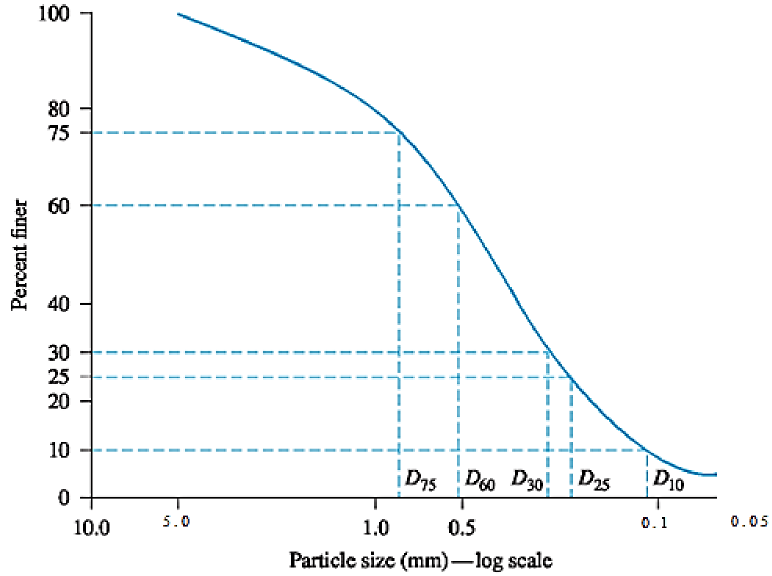


Figure (5.2) Definition of D_{60}, D_{30}, and D_{10}

The particle-size distribution curve shows not only the range of particle sizes present in a soil, but also the type of distribution of various-size particles. Such types of distributions are demonstrated in Figure (5.3). Curve I represents a type of soil in which most of the soil grains are the same size. This is called *poorly graded soil*. Curve II represents a soil in which the particle sizes are distributed over a wide range, termed *well graded*. A well-graded soil has a uniformity coefficient greater than about 4 for gravels and 6 for sands, and a coefficient of gradation between 1 and 3 (for gravels and sands). A soil might have a combination of two or more uniformly graded fractions. Curve III represents such a soil. This type of soil is termed *gap graded*.

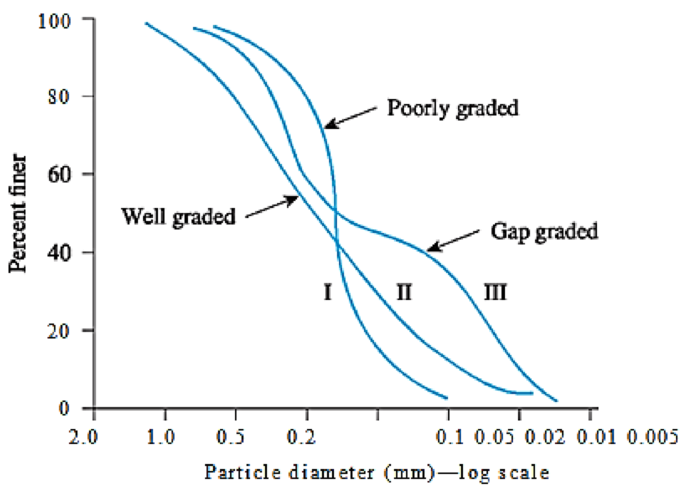


Figure (5.3) Different types of particle-size distribution curves

Example 5.1

Following are the results of a sieve analysis. Make the necessary calculations and draw a particle-size distribution curve.

U.S. sieve no.	Mass of soil retained on each sieve (g)
4	0
10	40
20	60
40	89
60	140
80	122
100	210
200	56
Pan	12

Solution

The following table can now be prepared.

U.S. sieve (1)	Opening (mm) (2)	Mass retained on each sieve (g) (3)	Cumulative mass retained above each sieve (g) (4)	Percent finer[a] (5)
4	4.75	0	0	100
10	2.00	40	0 + 40 = 40	94.5
20	0.850	60	40 + 60 = 100	86.3
40	0.425	89	100 + 89 = 189	74.1
60	0.250	140	189 + 140 = 329	54.9
80	0.180	122	329 + 122 = 451	38.1
100	0.150	210	451 + 210 = 661	9.3
200	0.075	56	661 + 56 = 717	1.7
Pan	–	12	717 + 12 = 729 = ΣM	0

[a] $\frac{\sum M - \text{col. 4}}{\sum M} \times 100 = \frac{729 - \text{col. 4}}{729} \times 100$

The particle-size distribution curve is shown in Figure 5.4

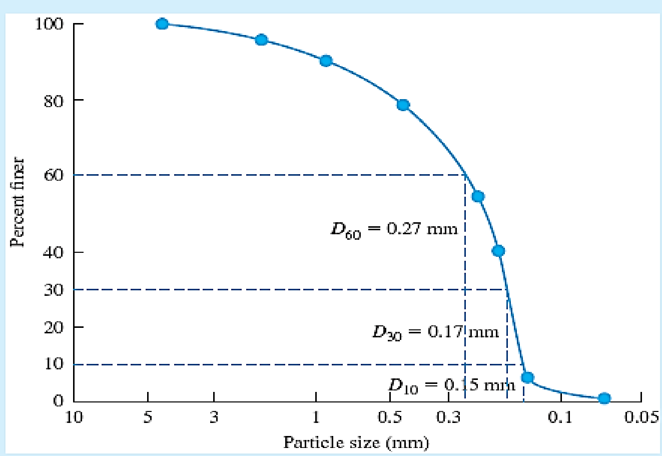


Figure (5.4) Particle-size distribution curve

Example 5.2

For the particle-size distribution curve shown in Figure (5.4) determine

a- D_{10}, D_{30}, and D_{60}
b- Uniformity coefficient, C_u
c- Coefficient of gradation, C_c

Solution

Part a

From Figure (5.4)

$$D_{10} = 0.15 \text{ mm}$$

$$D_{30} = 0.17 \text{ mm}$$

$$D_{60} = 0.27 \text{ mm}$$

Part b

$$C_u = \frac{D_{60}}{D_{10}} = \frac{0.27}{0.15} = 1.8$$

Part c

$$C_c = \frac{D_{30}^2}{D_{60} \times D_{10}} = \frac{(0.17)^2}{(0.27)(0.15)} = 0.71$$

Example 5.3

For the particle-size distribution curve shown in Figure (5.4), determine the percentages of gravel, sand, silt, and clay size particles persent. Use Unified Soil Classification system.

Solution

From Figure (5.4), we can prepare the following table.

Size (mm)	percent finer	
75	100	
		100 – 100 = 0% gravel
4.75	100	
		100 – 1.7 = 98.3% sand
0.075	1.7	
		1.7 – 0 = 1.7% silt and clay
-	0	

Example 5.4

An air dry soil sample weighing 2000g is brought to the soils laboratory for sieve analysis. The laboratory data are as follows:

U.S. sieve size	Size Opening (mm)	Weight Retained (g)
3/4 in.	19.0	0
3/8 in.	9.5	158
No. 4	4.75	308
No.10	2.00	608
No. 40	0.425	652
No. 100	0.150	224
No. 200	0.075	42
Pan	....	8

Plot the grain-size distribution curve for this soil sample.

Solution

(1) Sieve Number	(2) Sieve Opening (mm)	(3) Mass Retained (g)	(4) Cumulative Mass retained (g)	(5) Percentage Passing
3/4 in.	19.0	0	0	100
3/8 in.	9.5	158	158	92.1
No. 4	4.75	308	466	76.7
No.10	2.00	608	1074	46.3
No. 40	0.425	652	1726	13.7
No. 100	0.150	224	1950	2.5
No. 200	0.075	42	1992	0.4
Pan	....	8	ΣM = 2000	

$$col.(5) = \frac{\Sigma M - col.(4)}{\Sigma M} \times 100$$

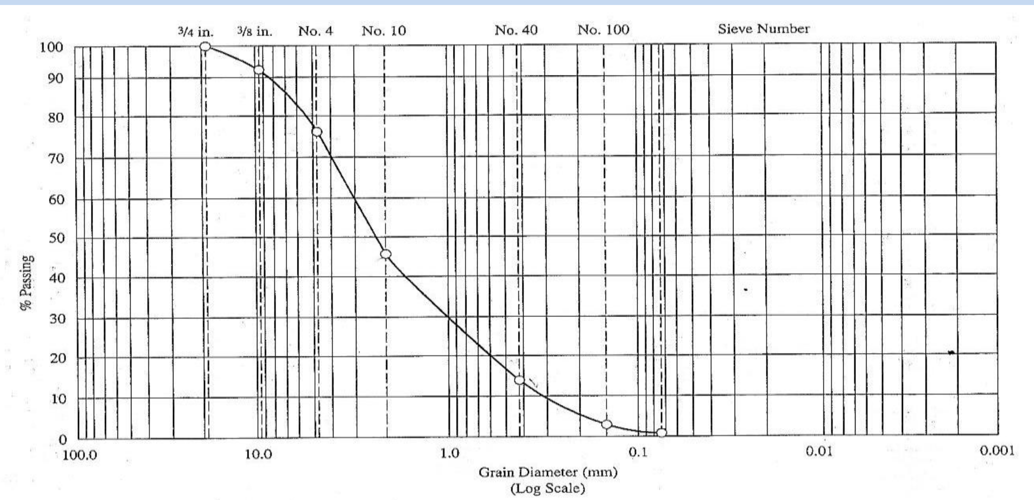


Figure (5.5) Grain-size Distribution curve for Example (5.4)

5.3 Unified Soil Classification System (ASTM D-2487)

The original form of this system was proposed by Casagrande in 1942 for use in the airfield construction works undertaken by the Army Corps of Engineers during World War II. In cooperation with the U.S. Bureau of Reclamation, this system was revised in 1952. At present, it is used widely by engineers (ASTM Test Designation D-2487). The Unified classification system is presented in Figures (5.6 through 5.8).

This system classifies soils into two broad categories:

1. Coarse-grained soils that are gravelly and sandy in nature with less than 50% passing through the No. 200 sieve. The group symbols start with a prefix of G or S. G stands for gravel or gravelly soil, and S for sand or sandy soil.
2. Fine-grained soils are with 50% or more passing through the No. 200 sieve. The group symbols start with prefixes of M, which stands for inorganic silt, C for inorganic clay, or O for organic silts and clays. The symbol Pt is used for peat, muck, and other highly organic soils.

Other symbols used for the classification are:

- W—well graded
- P—poorly graded
- L—low plasticity (liquid limit less than 50)
- H—high plasticity (liquid limit more than 50)

For proper classification according to this system, some or all of the following information must be known:

1. Percent of gravel—that is, the fraction passing the 75-mm sieve and retained on the No. 4 sieve (4.75-mm opening)
2. Percent of sand—that is, the fraction passing the No. 4 sieve (4.75-mm opening) and retained on the No. 200 sieve (0.075-mm opening)
3. Percent of silt and clay—that is, the fraction finer than the No. 200 sieve (0.075-mm opening)
4. Uniformity coefficient (C_u) and the coefficient of gradation (C_c)
5. Liquid limit and plasticity index of the portion of soil passing the No. 40 sieve

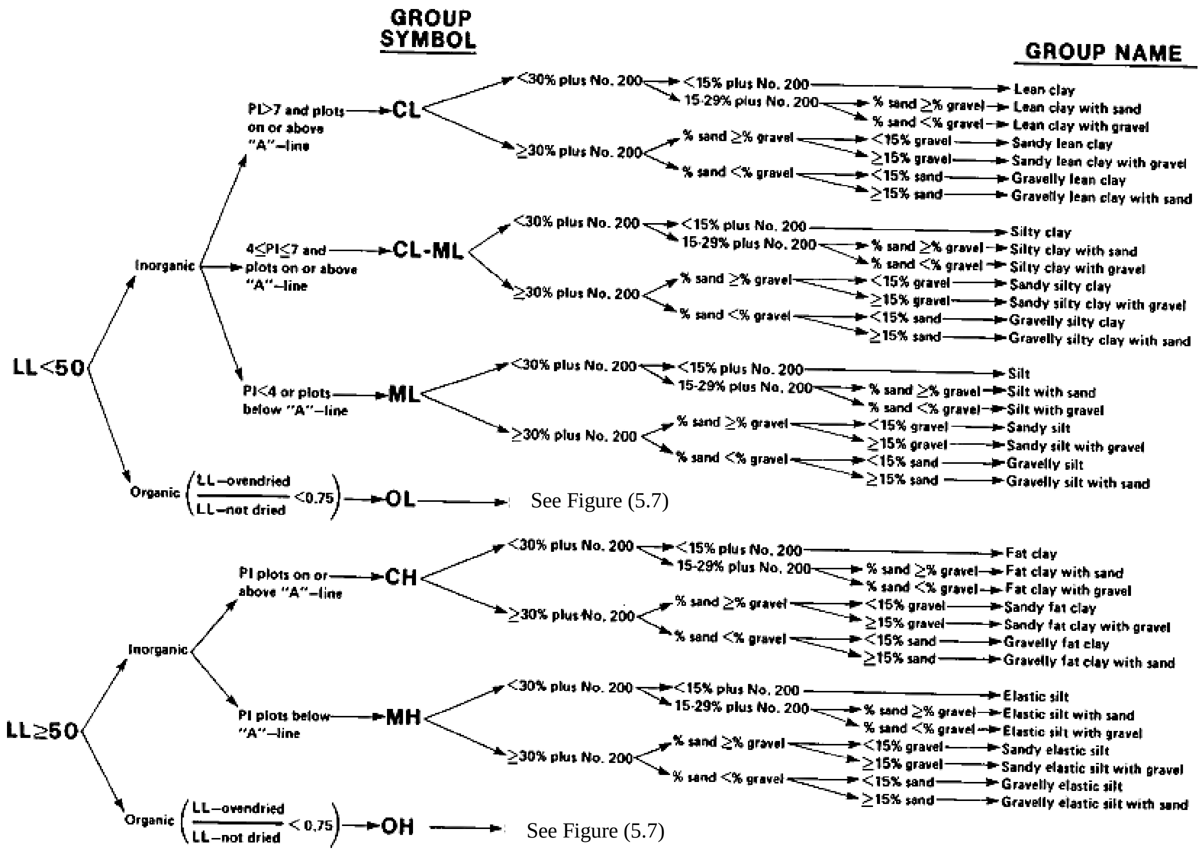


Figure (5.6) flow chart for classifying fine-grained soil (50% or more passes No. 200 sieve)

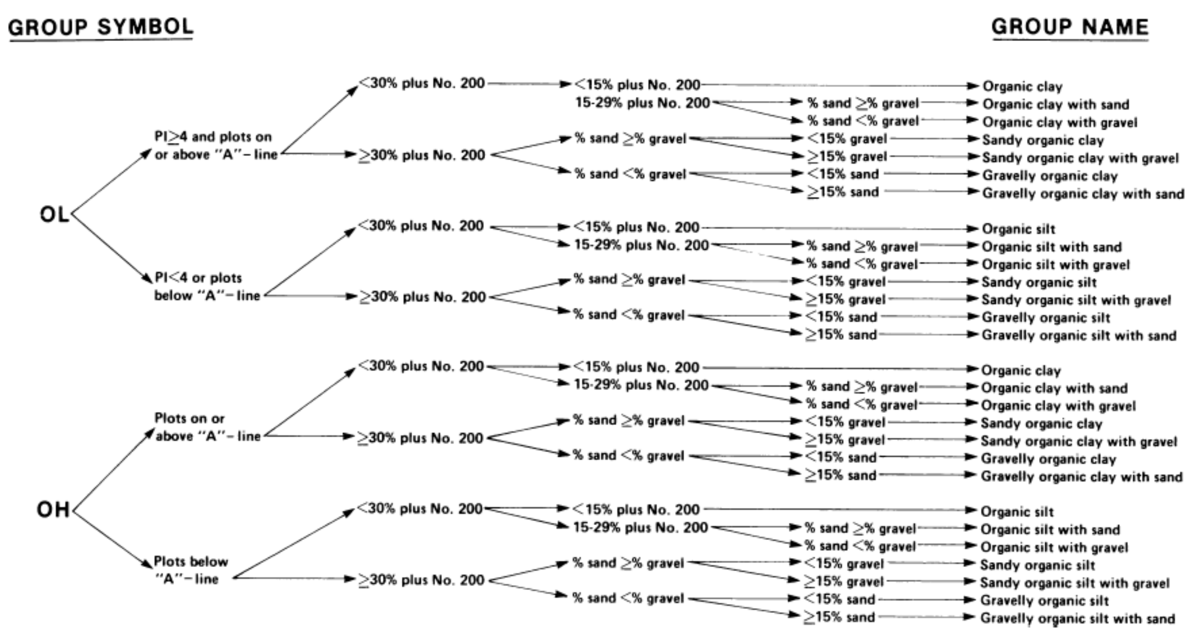


Figure (5.7) flow chart for classifying organic fine-grained soil (50% or more passes No. 200 seive)

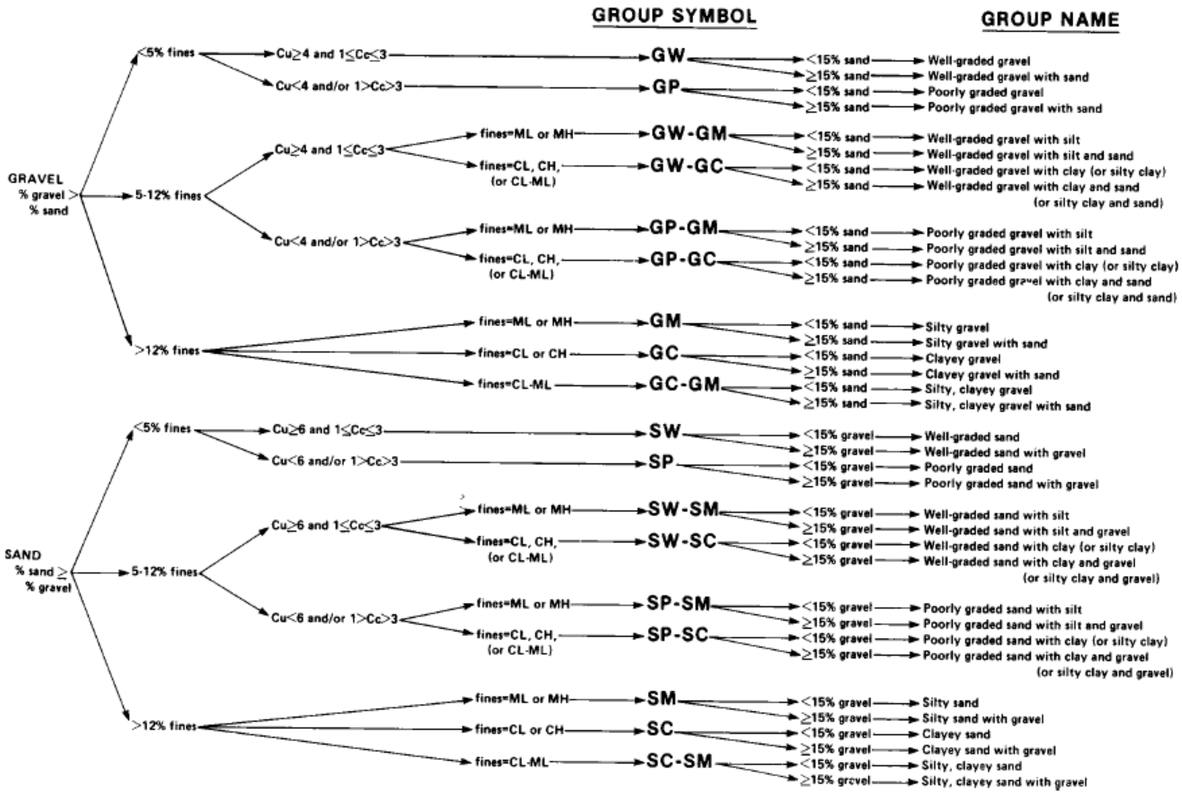


Figure (5.8) flow chart for classifying coarse -grained soils (More than 50% retained on No. 200 seive)

Example 5.5

A sample of soil was tested in the laboratory with the following results:

1- Liquid limit = 30.0 %
2- Plastic limit = 12.0 %
3- Sieve analysis data:

U.S. sieve size	Percentage Passing
3/8 in.	100
No. 4	76.5
No. 10	60.0
No. 40	39.7
No. 200	15.2

Classify the soil by the USCS.

Solution

Gravel; $P_{3/4} - P_4 = 100 - 76.5 = 23.5\%$

or $(R_4 - R_{3/4})$

Sand; $P_4 - P_{200} = 76.5 - 15.2 = 61.3\%$

or $(R_{200} - R_4)$

Fines; $P_{200} = 15.2\%$

Fines < 50% ⇒ Go to (**coarse-grained soils**) chart

Sand > Gravel ⇒ Go to (**sand**) block

Fines > 12% ⇒ consider plasticity chart

Plasticity chart

L.L = 30.0

P.I = 30.0 – 12 =18

} ⇒ Point above A-line ⇒ CL

Group symbol ≡ **SC**

Gravel ≥ 15% ⇒ (**clayey sand with gravel**)

⇒ The soil is **: clayey sand with gravel (SC)**

Example 5.6

A sample of soil was tested in the laboratory with the following results:

1- Liquid limit = NP (nonplastic)
2- Plastic limit = NP (nonplastic)
3- Sieve analysis data:

U.S. sieve size	Percentage Passing
1 in.	100
3/4 in.	85
1/2 in.	70
3/8in.	60
No. 4	48
No. 10	30
No. 40	16
No.100	10
No. 200	2

Classify the soil by the USCS.

Solution

Gravel: $P_{3''} - P_4 = 100 - 48 = 52$ %
Sand: $P_4 - P_{200} = 48 - 2 = 46$ %
Fines: $P_{200} = 2$ %
Fines < 50% ⇒ Go to (**coarse-grained soils**) chart

Gravel > Sand ⇒ Go to (**Gravel**) block

Fines < 5% ⇒ C_u and C_c need to be calculated.

From the particle size distribution curve:

$$C_u = \frac{D_{60}}{D_{10}} = \frac{9.5}{0.15} = 63.3$$

$$C_c = \frac{D_{30}^2}{D_{60}.D_{10}} = \frac{(2.0)^2}{(9.5)(0.15)} = 2.8$$

$C_u \geq 4$ and $1 \leq C_c \leq 3$ ⇒ Group symbol ≡ **GW**

Sand ≥ 15 ⇒ (Well-graded gravel with sand)

⇒ The soil is : **well-graded gravel with sand (GW)**

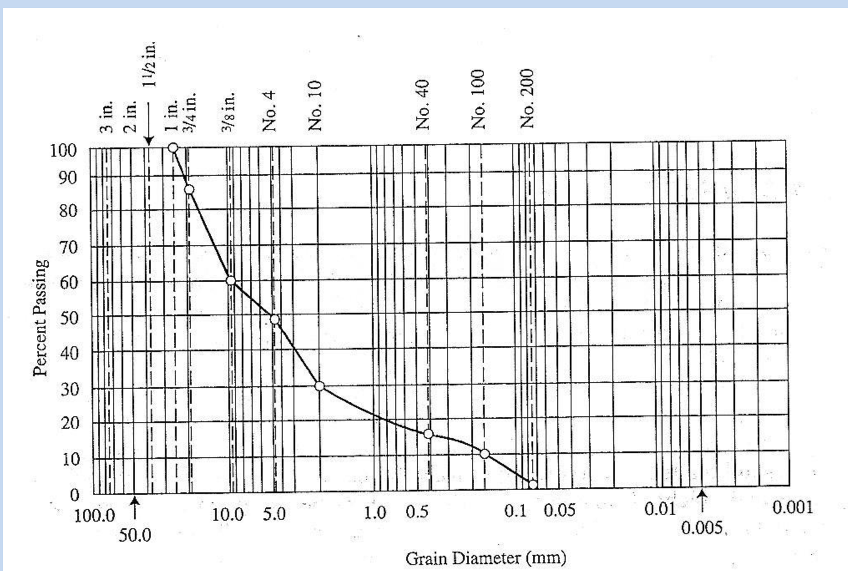


Figure (5.9) Grain-size Distribution curve for Example (5.6)

Example 5.7

A sample of inorganic soil was tested in the laboratory with the following results:

4- Liquid limit = 42.3 %
5- Plastic limit = 15.8 %
6- Sieve analysis data:

U.S. sieve size	Percentage Passing
No. 4	100
No. 10	93.2
No. 40	81.0
No. 200	60.2

Classify the soil sample by the USCS.

Solution

Gravel: $P_{3''} - P_4 = 100 - 100 = 0$
Sand: $P_4 - P_{200} = 100 - 60.2 = 39.8$ %
Fines: $P_{200} = 60.2$ %
Fines > 50% ⇒ Go to (**Fine-grained soils**) chart

L.L = 42.3% < 50

Inorganic soil

Plasticity chart

L.L = 42.3 %

P.I = 42.3 – 15.8 = 26.5% > 7.0

} Point above A-line

Group symbol ≡ **CL**

Plus No.200 (coarce-grained soil) = (0 + 39.8) = 39.8% > 30%

% sand > % gravel

% gravel < 15%

⇒ **Sandy lean clay (CL)**

Example 5.8

Figure (5.10) gives the grain-size distribution of two soils. The liquid and plastic limits of minus No. 40 sieve fraction of the soil are as follows:

	Soil A	Soil B
Liquid limit	30	26
Plastic limit	22	20

Determine the group symbols and group names according to the Unified soil Classification system.

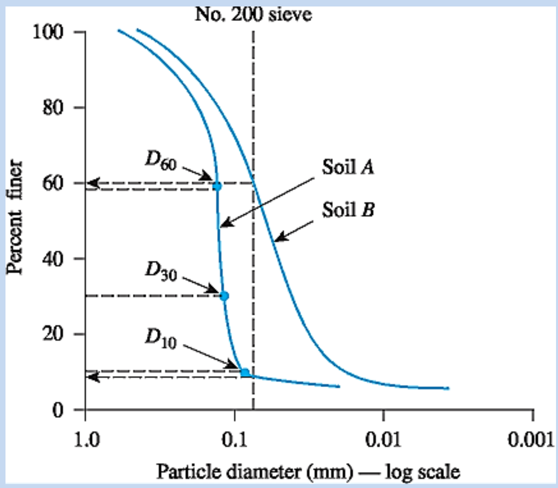


Figure (5.10) Particle –size distribution of two soils

Solution

<u>Soil A</u>

P_{200} = 8%

P_4 = 100%

$P_{3''}$ = 100%

Gravel = $P_{3''} - P_4$ = 0

Sand = $P_4 - P_{200}$ = 100 – 8 = 92%

Fines = P_{200} = 8%

Fines < 50% ⇒ Goto (**Coarse-grained soils**) chart

Gravel < Sand ⇒ Goto (**Sand**) block

5 < Fine < 12% ⇒ C_u and C_c need to be calculated

From the Figure (5.10);
D_{10} = 0.085 mm, D_{30} = 0.12 mm, D_{60} = 0.135 mm. Thus ;

$$C_u = \frac{D_{60}}{D_{10}} = \frac{0.135}{0.085} = 1.59 \ < 6$$

$$C_c = \frac{D_{30}^2}{D_{60}.D_{10}} = \frac{(0.12)^2}{(0.135)(0.085)} = 1.25 \ > 1$$

⇒ **Poorly graded sand**

Plasticity chart

LL = 30
PI = 30 – 22= 8

⇒ Point above A-line (CL)

Group symbol ≡ SP-SC

Gravel < 15% ⇒ **poorly graded sand with clay**
⇒ The soil is: poorly graded sand with clay (SP-SC)

<u>Soil B</u>

P_{200} = 61%

P_4 = 100%

$P_{3''}$ = 100%

Gravel = $P_{3''}$ – P_4 = 0

Sand = P_4 – P_{200} = 100 – 61 = 39%

Fines = P_{200} = 61%

Fines > 50% ⇒ Goto (**Fine-grained soils**) chart

Plasticity chart

LL = 26
PI = 26 – 20= 6

Group symbol ≡ CL-ML

Plus No.200 = 100– 61 = 39% > 30%

Sand > Gravel

Gravel < 15%

⇒ (**Sandy silty clay**)

The soil is : Sandy silty clay (CL-ML)

Example 5.9

For a given soil, the following are known:

- Percentage passing 3″ = 100
- Percentage passing No. 4 sieve = 70
- Percentage passing No. 200 sieve = 30
- Liquid limit = 33
- Plastic limit = 12

Classify the soil using the Unified Soil Classification system. Given the group symbol and the group name.

Solution

$P_{200} = 30\%$

$P_4 = 70\%$

$P_{3''} = 100\%$

Gravel = $P_{3''} - P_4 = 30\%$

Sand = $P_4 - P_{200} = 70 - 30 = 40\%$

Fines = $P_{200} = 30\%$

Fines < 50% ⇒ Goto (**Coarse-grained soils**) chart

Sand > Gravel ⇒ Goto (**Sand**) block

Fines = 30% ⇒ consider plasticity chart

Plasticity chart

$LL = 33$
$PI = 33 - 12 = 21$

} ⇒ above A-line (CL)

Group symbol ≡ SC

Gravel >15% **⇒ Clayey sand with gravel**
⇒ The soil is: Clayey sand with gravel (SC)

Problems

5.1 For a soil, suppose that D_{10} = 0.08 mm, D_{30} = 0.22 mm, and D_{60} = 0.41 mm. Calculate the uniformity coefficient and the coefficient of gradation.

Ans: C_u = 5.13, C_c = 1.48

5.2 Repeat (Problem **5.1**) with the following: D_{10} = 0.24 mm, D_{30} = 0.82 mm, and D_{60} =1.81 mm.

Ans: C_u = 7.54, C_c = 1.55

5.3 Repeat (Problem **5.1**) with the following: D_{10} = 0.18 mm, D_{30} = 0.32 mm, and D_{60} = 0.78 mm.

Ans: C_u = 4.33, C_c = 0.73

5.4 The following are the results of a sieve analysis:

U.S. sieve No.	Mass of soil retained (g)
4	0
10	18.5
20	53.2
40	90.5
60	81.8
100	92.2
200	58.5
pan	26.5

a. Determine the percent finer than each sieve and plot a grain-size distribution curve.
b. Determine D_{10}, D_{30}, and D_{60} from the grain-size distribution curve.
c. Calculate the uniformity coefficient, C_u.
d. Calculate the coefficient of gradation, C_c.

Ans: (b) D_{10} = 0.12mm, D_{30} =0.21mm, and D_{60}=0.41mm (c) C_u=3.42 (d) C_c= 0.9

5.5 Repeat Problem 5.4 with the following:

U.S. sieve No.	Mass of soil retained (g)
4	0
10	44
20	56
40	82
60	51
80	106
100	92
200	85
pan	35

Ans: (b) D_{10} =0.089mm, D_{30} =0.18mm, D_{60}=0.29mm (c) C_u=3.26 (d) C_c= 1.26

5.6 Repeat Problem 5.4 with the following:

U.S. sieve No.	Mass of soil retained (g)
4	0
10	41.2
20	55.1
40	80.0
60	91.6
100	60.5
200	35.6
pan	21.5

Ans: (b) D_{10} = 0.13mm, D_{30} =0.26mm, D_{60}=0.51mm (c) C_u=3.92 (d) C_c= 1.02

5.7 Repeat Problem 5.4 with the following:

U.S. sieve No.	Mass of soil retained (g)
4	0
6	0
10	0
20	9.1
40	249.4
60	179.8
100	22.7
200	15.5
pan	23.5

Ans: (b) D_{10} = 0.23mm, D_{30} =0.33mm, D_{60}=0.48mm (c) C_u=2.09 (d) C_c= 0.99

5.8 The particle-size characteristics of a soil are given in this table. Draw the particle-size distribution curve.

Size (mm)	Percent
0.425	100
0.033	90
0.018	80
0.01	70
0.0062	60
0.0035	50
0.0018	40
0.001	35

Determine the percentages of gravel, sand, silt, and clay:According to the USDA system.

Ans: Gravel=0%, Sand = 6%, Silt = 52%, Clay = 42%

5.9 In a hydrometer test, the results are as follows: G_s = 2.60, temperature of water = 24 °C, and R = 43 at 60 min after the start of sedimentation (see Figure 2.24). What is the diameter, D, of the smallest-size particles that have settled beyond the zone of measurement at that time (that is, t = 60 min)?

Ans; D = 0.0052 mm

5.10 Repeat Problem 5.9 with the following values: G_s = 2.70, temperature = 23 °C, t = 120 min, and R = 25.

Ans: D = 0.0041 mm

5.11 Classify the following soil using the U.S. Department of Agriculture textural classification chart.

	Particle-size distribution (%)		
Soil	Sand	Silt	Clay
A	20	20	60
B	55	5	40
C	45	35	20
D	50	15	35
E	70	15	15

Ans:

Classification of soil				
A	B	C	D	E
Clay	Sandy clay	Loam	Sandy clay loam	Sandy loam

5.12 Classify the following soils using the Unified soil classification system. Give group symbols and group names.

Soil No.	Sieve analysis (percent finer) No.4	No. 200	Liquid limit	Plasticity limit	Comments
1	94	3	—	NP	C_u = 4.48 and C_c = 1.22
2	100	77	63	25	
3	100	86	55	28	
4	100	45	36	22	
5	92	48	30	8	
6	60	40	26	4	
7	99	76	60	32	

Ans:

Soil	Symbol	Group name
1	SP	Poorly graded sand
2	MH	Elastic silt with sand
3	CH	Fat clay
4	SC	Clayey sand
5	SC	Clayey sand
6	GM-GC	Silty clayey gravel with sand
7	CH	Fat clay with sand