Module 2: Index properties (Part 2)

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Spring 2022

January 28, 2022

COURSE CONTENTS AND SCHEDULE

Department of
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Tentative schedule

Day	Date	Topic	Lab.
W	1/19/2022	Class introduction, syllabus, policies	Soil
F	1/21/2022	Invited speaker: Topic TBD	components
M	1/24/2022	Introduction: The geological cycle, soil origin	Grain size
W	1/26/2022	Introduction: Site investigation	dist.
F	1/28/2022	Index properties: Phase relationships	
M	1/31/2022	Index properties: Grain size distribution, Atterberg limits	Atterberg
W	2/2/2022	Index properties: Soil classification	limits
F	2/4/2022	Compaction	
M	2/7/2022	Quiz 1: Introduction, index properties, compaction, in-situ testing	Visual
W	2/9/2022	Water in soils: Groundawater table, pore pressure, total and effective stresses	classification
F	2/11/2022	Water in soils: Darcy's law	
M	2/14/2022	Water in soils: Permeability and hydraulic conductivity	Compaction
W	2/16/2022	Water in soils: One-dimensional seepage	
F	2/18/2022	Water in soils: 2D-3D seepage, flow nets, pore pressure, uplift force, seepage force	
M	2/21/2022	President's day: no class	In-situ
W	2/23/2022	Water in soils: piping	density
F	2/24/2022	Quiz 2: Water in soils	
M	2/28/2022	Induced stress: Approximations, Bousinesq's elastic solution	Permeability
W	3/2/2022	Induced stress: Bousinesq's elastic solution, superposition	
F	3/4/2022	Induced stress: Stress tensor, elastic deformations	
M	3/7/2022	Consolidation: Oedometer test, primary and secondary consolidation	Site
W	3/9/2022	Consolidation: Preconsolidation pressure, OCR	investigation
F	3/11/2022	Consolidation: Primary consolidation parameters	
M	3/14/2022	Spring break: no class	
W	3/16/2022	Spring break: no class	
F	3/18/2022	Spring break: no class	
M	3/21/2022	Consolidation: rate of consolidation	Bonus
W	3/23/2022	Consolidation: preloading, radial consolidation	
F	3/25/2022	Quiz 3: Induced stress and consolidaiton	
M	3/28/2022	State of stress: 2D stresses and Mohr's circle	Consolidation
W	3/30/2022	State of stress: principal stresses, stress invariants, rotations	
F	4/1/2022	State of stress:: Usage of Mohr's circle	
M	4/4/2022	State of stress: stress paths, simple shear, triaxial compression	Settlement
W	4/6/2022	Quiz 4: State of stress	estimates
F	4/8/2022	Shear strength: Mohr-Coulomb failure criteria	
M	4/11/2022	Shear strength: drained and undrained behavior	Unconfined
W	4/13/2022	Shear strength: Shear strength of clays	compression
F	4/15/2022	Shear strength: Shear strength of sands	test
M	4/18/2022	Quiz 5: Shear strength	Direct
W	4/20/2022	Lateral earth pressure: at-rest, passive, and active conditions [2]	shear
F	4/22/2022	Intro to slope stability [2]	
M	4/25/2022	Intro to bearing capacity [2]	Direct
W	4/27/2022	Maine's day: no class	shear
F	4/29/2022	Classes end: Q&A session	
M	5/2/2022	Final exam (1:30 PM- 3:30 PM) Williams Hall 110	

M: Monday - W: Wednesday - F: Friday

[2] This items may or may not be covered. It will be determined by how far the course has progressed.

RECAP

- We discussed phase diagrams and their use.
- Three possible saturation states: Dry, partially saturated, and fully saturated.
- We learned to measure soil voids using void ratio and porosity.
- We learned to measure water in soils using saturation, gravimetric, and volumetric water content.
- We derived expressions relating unit weights, saturation, void ratio, and water content.
- Today we will learn about sieve analysis and Atterberg limits.

HOMEWORK ASSIGNMENT 2

- Due on 02/09/2022.
- 80 points total.
- Start ASAP.

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CIE-365 Spring 2022: Homework assignment 2

Due date: 02/09/2022 at 10:00 AM
Possible points: 80

Answer the following questions based on the contents of Module 2.

1. [O1] (10 points) Using phase diagrams derive equations 1, and 2:

$$\gamma_t = G_s \gamma_w (1 - n) + nS\gamma_w \tag{1}$$

$$\gamma_t = G_s \gamma_w (1 - n)(1 + w) \tag{2}$$

where γ_t is the total or moist unit weigh, G_s is the specific gravity, γ_w is the water unit weight, n is the porosity, S is the degree of saturation, and w is the water content.

2. [O1] (5 points) A sand has a natural water content of 5% and a total unit weight of $\gamma_t = 18.0$ kN/m^3. The void ratios corresponding to the densest and loosest state of this soil are $e_{min} = 0.51$ and $e_{max} = 0.87$ respectively. Find the relative density and degree of saturation.

3. [O1] (5 points) A saturated clay encountered in a deep excavation has a water content of $w = 25\%$. Determine the void ratio and saturated unit weight, knowing that $G_s = 2.70$.

4. [O1] (15 points) A laboratory test determined that the minimum and maximum void ratios of some gravel are $e_{min} = 0.2$ and $e_{max} = 0.95$ respectively. In a construction site, the gravel was used as fill for a 20m long retaining wall shown in figure 1. It was determined that the in-situ moist unit weight was $\gamma_t = 20$kN/m^3 with a moisture content of $w = 8\%$. a) Determine the in-situ void ratio of the gravel, b) its relative density, c) minimum and maximum dry densities. d) If the gravel is transported from its source with a relative density of $D_r = 23\%$ and moisture content of $w = 1\%$, what is the volume of gravel transported from its source to the site?. Use $G_s = 2.67$.

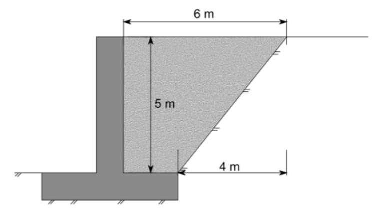


Figure 1: Sketch of retaining wall geometry for problem 4.

5. [O1] (3 points) Table 1 shows results obtained from a liquid limit test on a clay using the Casagrande cup device.

   (a) Determine the liquid limit of this clay.

CONTENTS

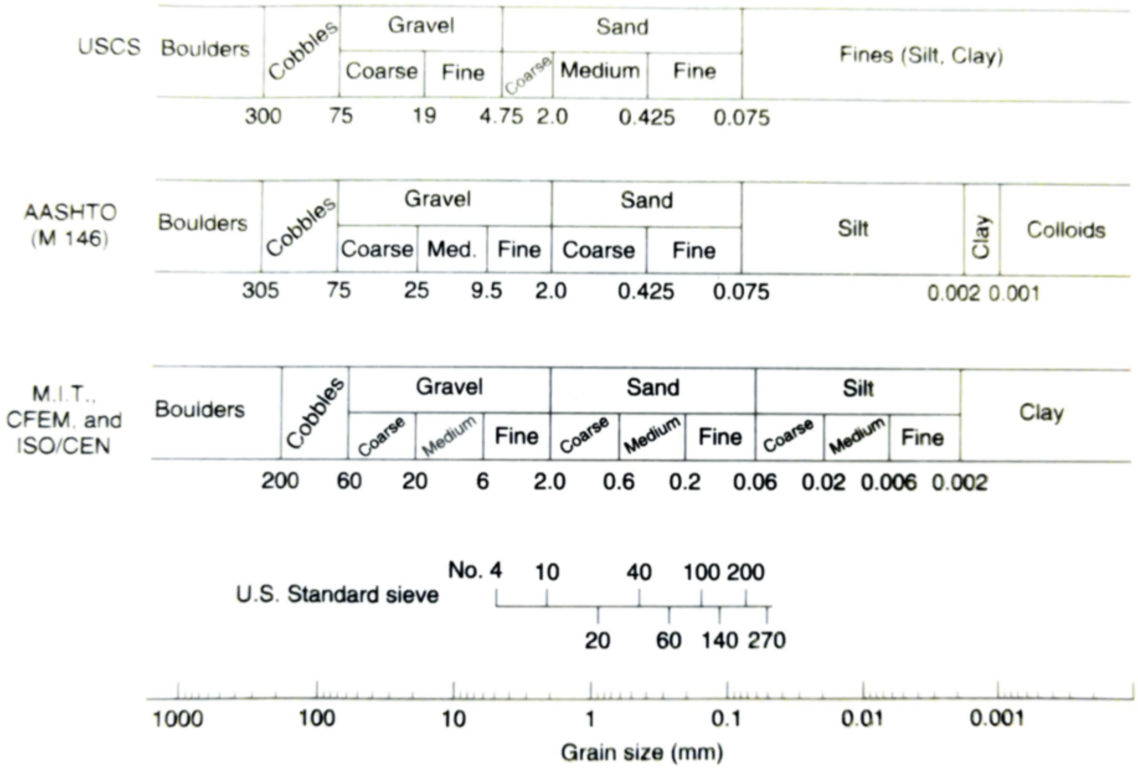
- Sieve and hydrometer analysis
- Grain size distribution (GSD)
- GSD metrics
- Specific surface
- Clay mineralogy
- Atterberg limits and activity
- Soil classification

More in chapter 2 and 4 of Holtz et al. (2013)

GRAIN SIZE CHARACTERISTICS

Soil name:	Gravels, Sands	Silts	Clays
Grain size:	Coarse grained Can see individual grains by eye	Fine grained Cannot see individual grains	Fine grained Cannot see individual grains
Characteristics:	Cohesionless Nonplastic Granular	Cohesionless Nonplastic Granular	Cohesive Plastic —
Effect of water on engineering behavior:	Relatively unimportant (exception: loose saturated granular materials and dynamic loadings)	Important	Very important
Effect of grain size distribution on engineering behavior:	Important	Relatively unimportant	Relatively unimportant

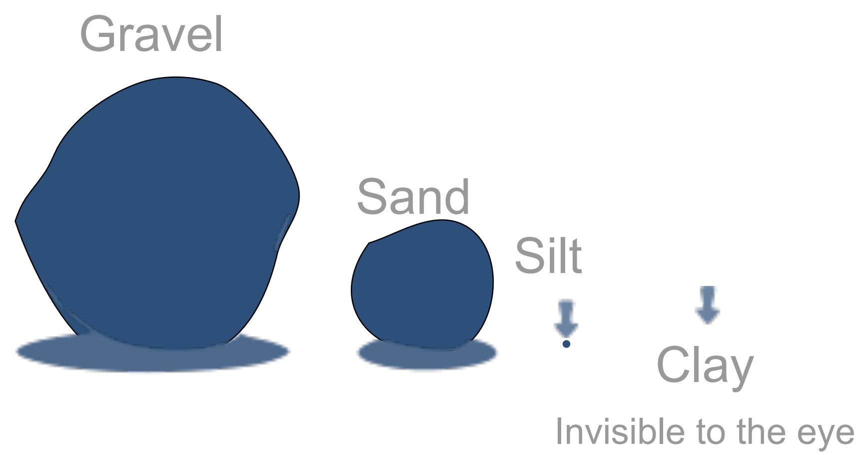
GRAIN SIZE CHARACTERISTICS



USCS = Unified Soil Classification System (U.S. Bureau of Reclamation, 1974; U.S. Army Engineer WES, 1960); ASTM D 2487

AASHTO = American Association for State Highway and Transportation Officials (1998)

M.I.T, C.F.E.M., ISO/CEN = Massachusetts Institute of Technology (Taylor, 1948); Canadian Foundation Engineering Manual (2006); International Standardisation Organisation and Comité Européen de Normalisation.



SIEVE ANALYSIS (ASTM D6913)

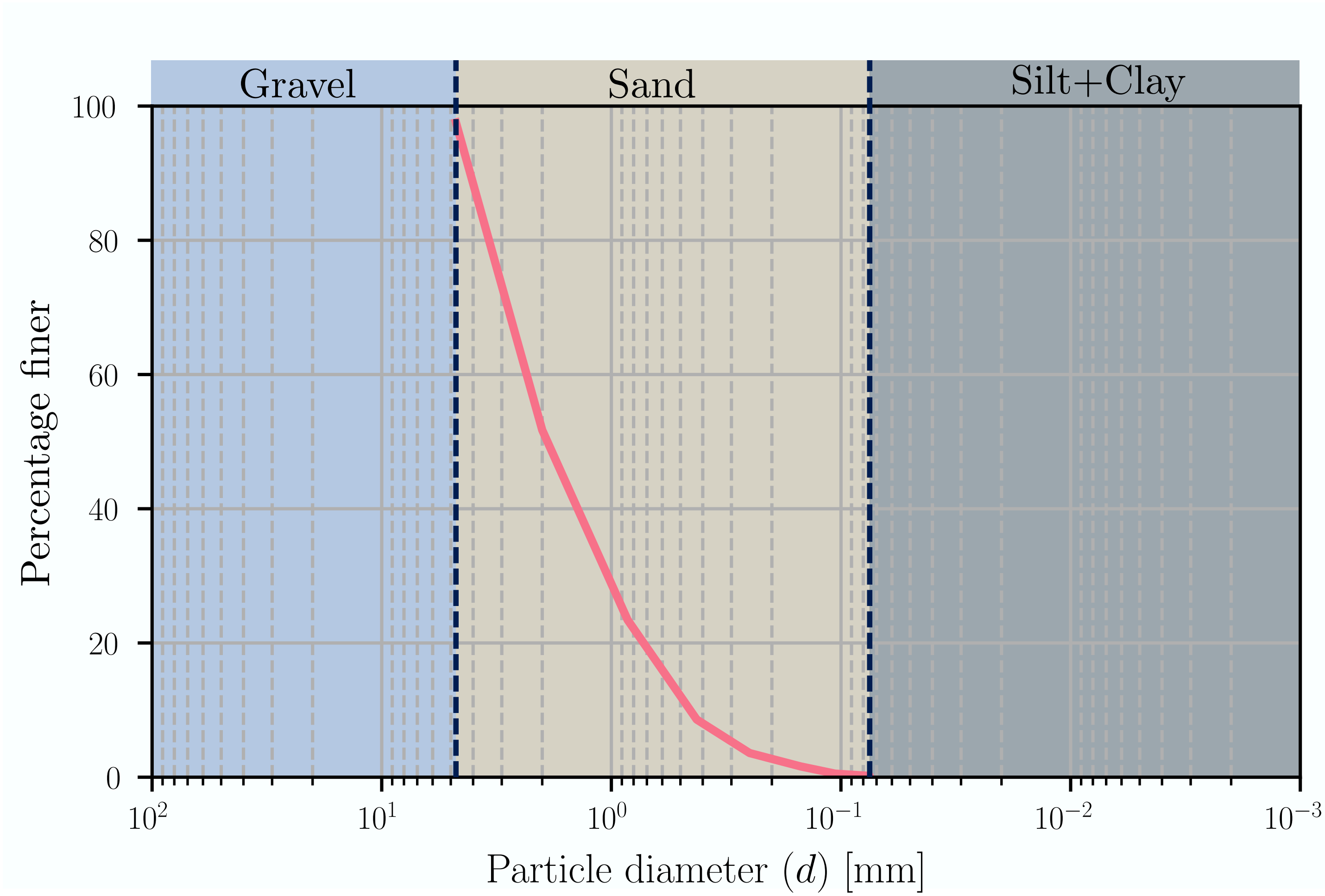
- Conducted on dry sample. Particles of different sizes are separated by meshes.
- Conducted for coarse soils only (gravels and sands $d > 0.075$ mm or sieve No 200).
- The individual weight retained in sieve i is measured (W_i).
- The percentage retained or coarser than sieve i is $R_i = \sum W_i / W_t$.
- The percentage passing or finner than sieve opening i is $P_i = 100 - R_i$.

U.S. Standard	Sieve Opening
Sieve No.	(mm)
4	4.75
10	2
20	0.85
40	0.425
60	0.25
100	0.15
140	0.106
200	0.075

EXAMPLE 2.4

Sieve Opening	Weight	Retained	Passing
(mm)	(g)	(%)	(%)
4.75	12.5		
2	233.67		
0.85	144.13		
0.425	75.75		
0.25	25.47		
0.15	10.14		
0.106	5.5		
0.075	1.7		
Pan	1		
Total	509.86		

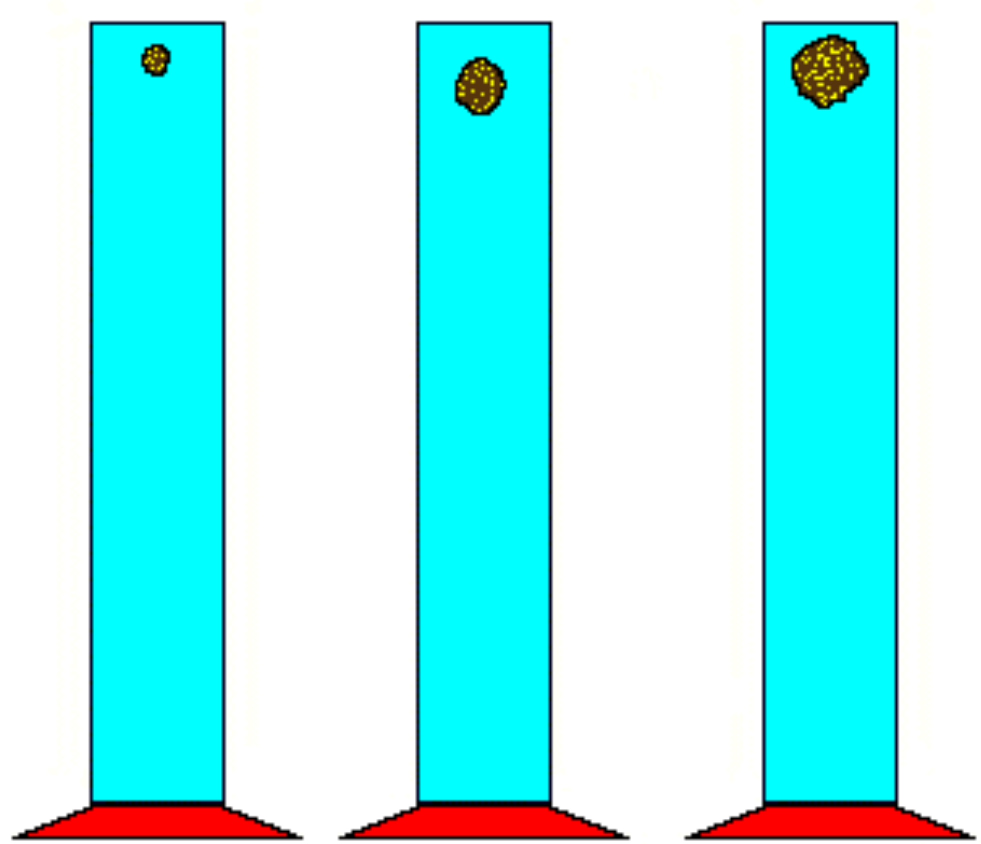
EXAMPLE 2.4



Gravel
Sand
Silt+Clay
100
80
60
40
20
0
Percentage finer
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
Particle diameter (d) [mm]

HYDROMETER ANALYSIS

- Separation of particles by sedimentation (Stokes law).
- Relative density of suspended flow is measured in time to determine particle diameter.
- Works for fine soils $(d < 0.075$ mm or passing No 200).
- Has several limitations due to unrealistic assumptions.



EXAMPLE 2.5: COMBINED GSD

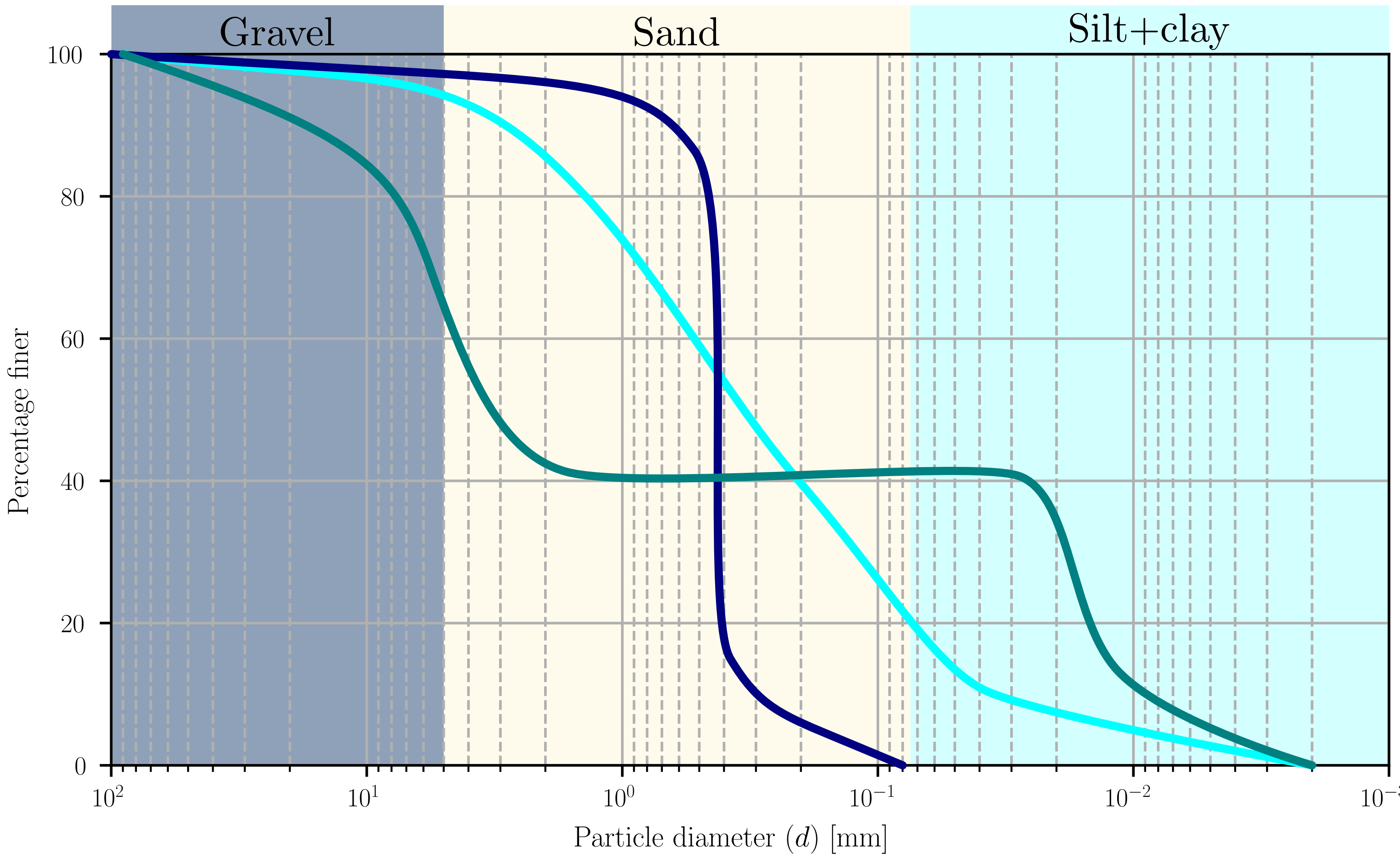
Sieve analysis

Sieve Opening	Weight	Retained	Passing
(mm)	(g)	(%)	(%)
4.75	0	0.0%	100.0%
2	12.12	3.6%	96.4%
0.85	25.36	11.2%	88.8%
0.425	32.15	20.8%	79.2%
0.25	33.14	30.7%	69.3%
0.15	33.78	40.8%	59.2%
0.106	47.56	55.0%	45.0%
0.075	50.14	70.0%	30.0%
Pan	100.25	100.0%	0.0%
Total	334.5		

Hydrometer analysis

Part. Diameter	Percentage Finer
(mm)	%
0.066	85%
0.045	74%
0.036	68%
0.025	58%
0.015	48%
0.011	42%
0.007	35%
0.005	28%
0.004	24%
0.003	20%
0.0018	16%
0.0012	12%

GSD METRICS


Gravel
Sand
Silt+clay
100
80
60
40
20
0
Percentage finer
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
Particle diameter (d) [mm]

GSD METRICS

According to its gradation:

1. If GSD is vertical soil is uniform, or poorly graded, or well sorted.
2. If GSD spans all ranges of soil in a smooth curve the soil is well graded or poorly sorted.
3. If there is a horizontal line in the GSD, the soil is gap graded.

Soil fractions

- Gravel fraction G_F is the cumulative retained percentage in Sieve No 4 or $d > 4.75$ mm.
- Fine fraction F_F is the portion of soils that passes Sieve No 200.
- Sand fraction $S_F = 100 - G_F - F_F$ is the percentage of soil that passes Sieve No 4 and is retained in sieve No 200 or $0.075 < d \leq 4.75$ mm
- Clay fraction C_F is the portion of soils finer than 2 μm.

GSD METRCIS

Let's define D_x as the particle size for which x percent of soil is finer thant that diameter.

Common values are:

1. D_{10} also known as the effective diameter.
2. D_{30}.
3. D_{50} or median particle size.
4. D_{60}.

Gradation coefficients:

- Coefficient of uniformity C_u:

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

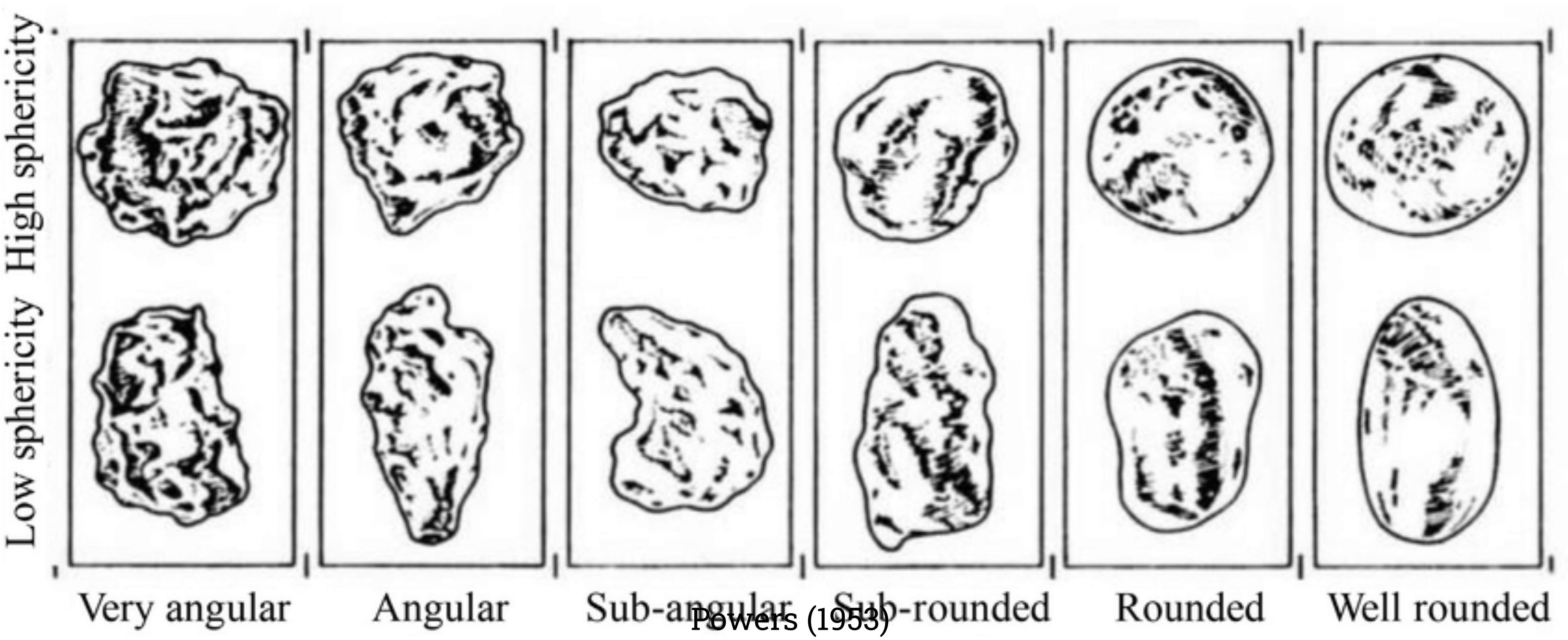
- Coefficient of curvature C_c:

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

EXAMPLE 2.6

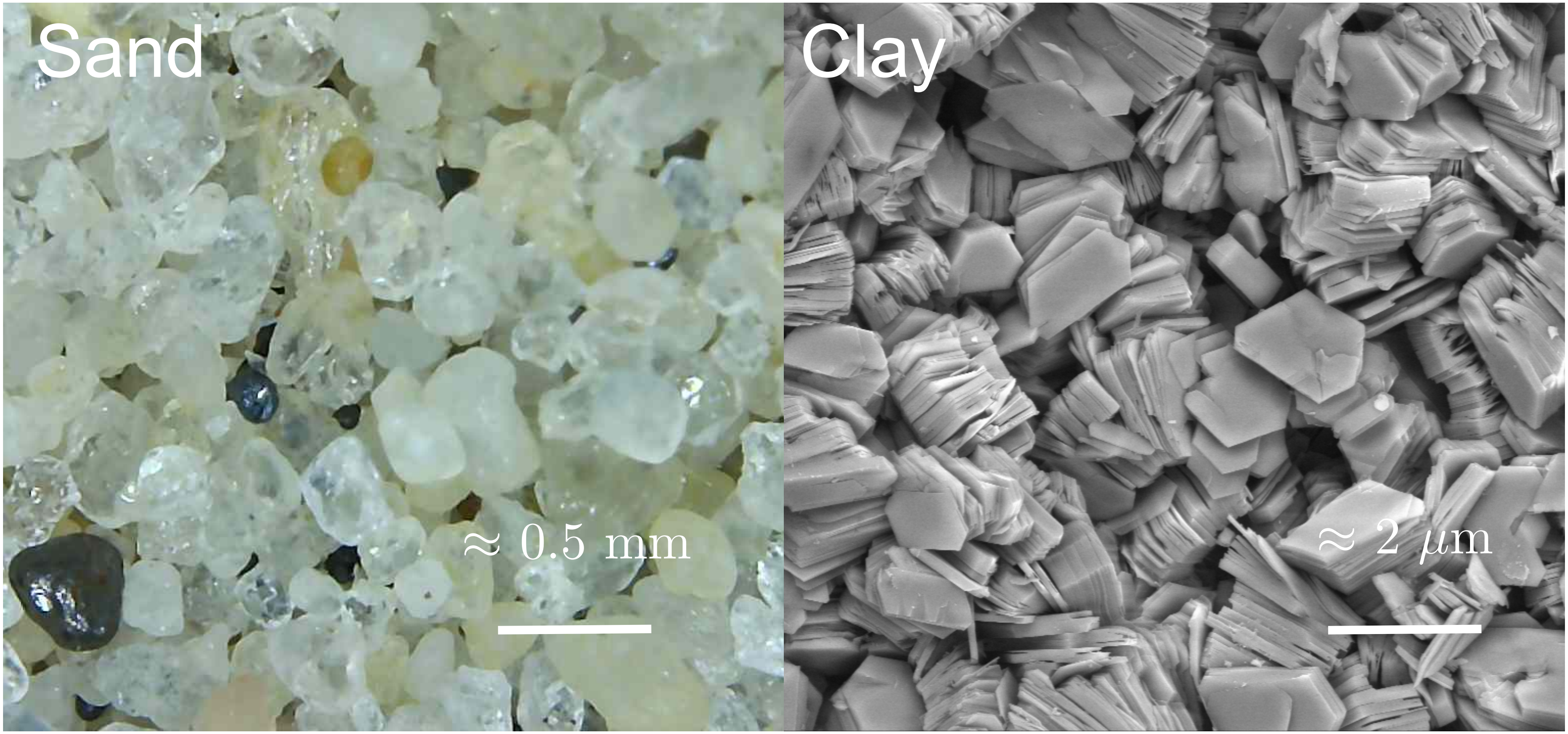
Determine the the soil fractions and gradation coefficients of soils 1, 2, and 3.

PARTICLE SHAPE



Powers (1953)

PARTICLE SHAPE

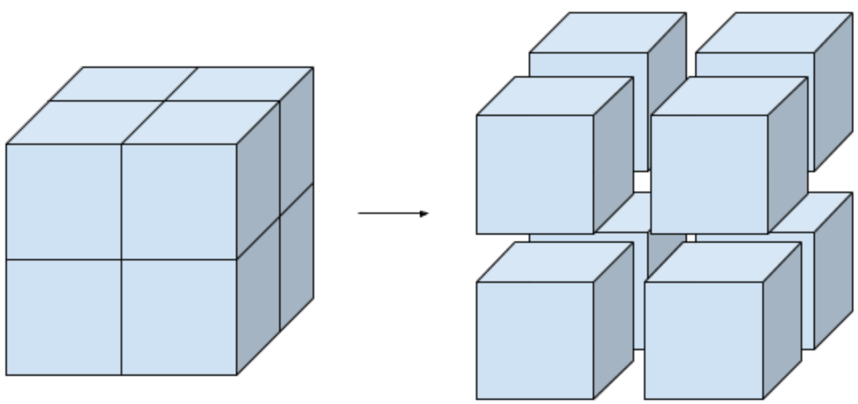


SPECIFIC SURFACE

Specific surface is defined as:

$$SSA = S_a / M$$

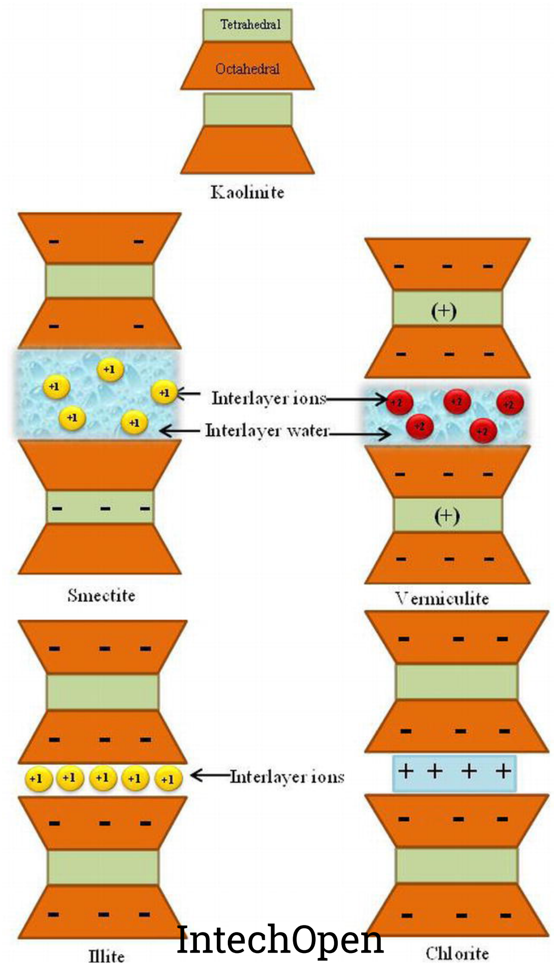
S_a= Surface area. M= mass



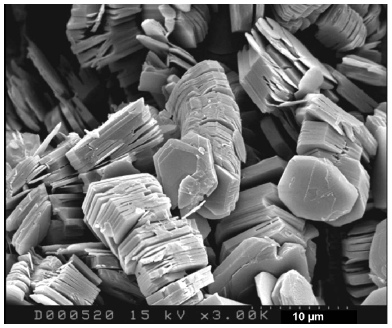
- Coarse particles have lower SSA than fine particles.
- A high SSA means more chemical and physical reactions.
- A high SSA means more area for drag. Finer soils are less permeable than coarse soils.

CLAY MINERALOGY

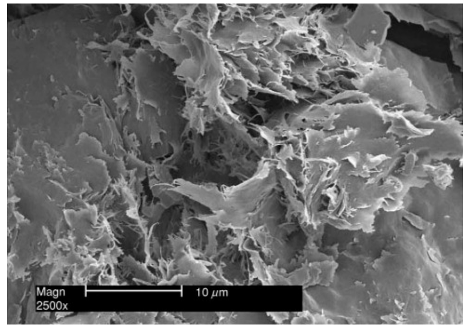
- Chemical weathering of rocks form phyllosilicates (hydrous aluminum silicates).
- Only visible with electron microscope and look like plates, flakes, or needles.
- Two simple blocks: tetrahedral silica and octahedral alumina.
- The main blocks are arranged in various ways to produce clay minerals.



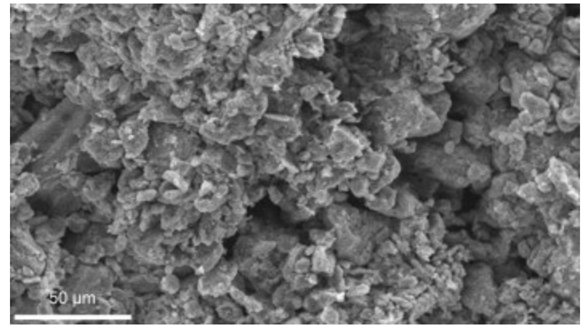
CLAY MINERALOGY



Kaolinite



Illite



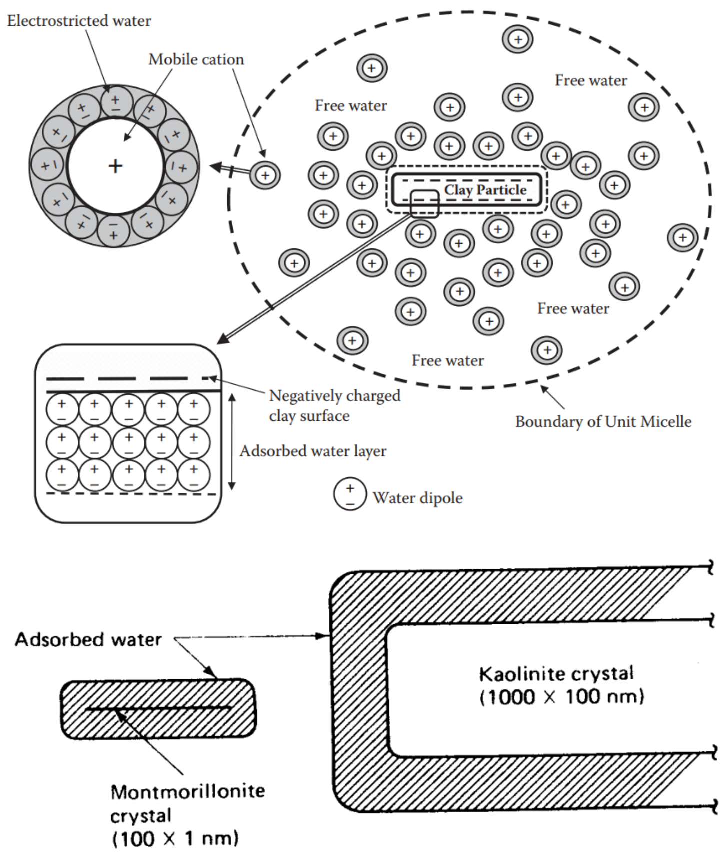
Montmorillonite

Comparison of Shapes and Surface Areas of Clays and Clay-Size Particles

Clay Type	Typical Length (L), μm	Typical Thickness (T) μm	Typical Dimensional Ratio (L : L : T)	Specific Surface m^2/g
Kaolinite	0.3–3	0.05–1	10 x 10 x 1	10–20
Illite	0.1–2	0.01–0.2	30 x 30 x 1	80–100
Montmorillonite	0.1–1	0.001–0.01	100 x 100 x 1	800
Sphere (1 μm dia.)	1	1	1 x 1 x 1	3
Sphere (0.1 μm dia.)	0.1	0.1	1 x 1 x 1	30

Ishibashi and Hazarika (2010)

INTERACTION OF CLAY WITH WATER



Ishibashi and Hazarika (2010) and Holtz et al. (2013)

- Stronger influence for minerals with large SSA.
- Interaction of negatively charged particle with water and cations will increase/decrease the diffuse double layer thickness.
- Changes in the DBL thickness can be seen macroscopically as swelling and shrinkage.
- Interaction with water also causes changes in consistency of fine soils.

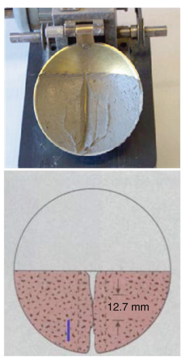
CONSISTENCY LIMITS

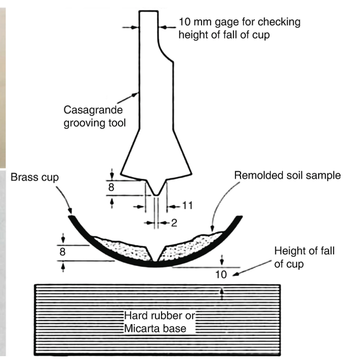
- Also known as Atterberg limits after the soil scientist who proposed them.
- They are thresholds of water content at which the behavior of fine soils changes.
- From experimentation he found three limits: the liquid limit LL, plastic limit PL, and the shrinkage limit SL.

Albert Atterberg.
Fotografi.

LIQUID LIMIT ASTM D4318

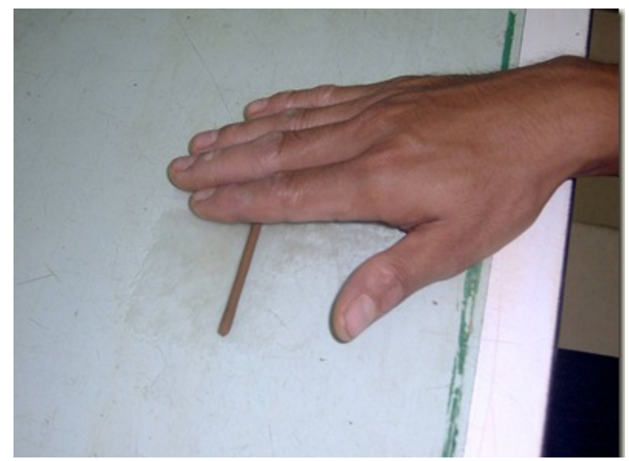
- Arthur Casagarnde proposed the modern test procedures.
- He defined LL as the water content at which a standard groove cut in the soil will close 0.5 in at 25 blows.
- Values from zero to 1000. Most soils have LL less than 100.





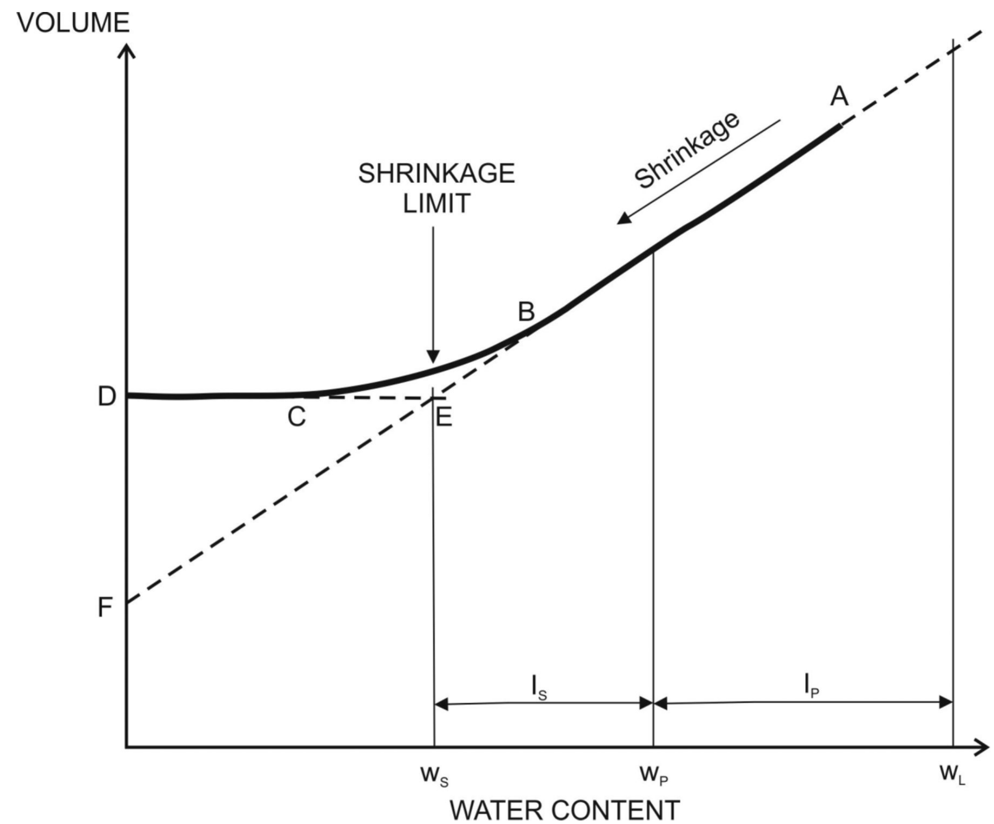
PLASTIC LIMIT ASTM D4318

- Defined as the water content at which a thread of soil just crumbles when rolled to a diameter of 3 mm.
- Requires more practice to obtain consistent and reproducible results.
- Ranges from zero to 100. Most soils have $PL < 40$.



SHRINKAGE LIMIT ASTM D4943

- Defined as the water content at which no more volume change occurs when soil is desiccated.
- Module 4 will expand on this.



Hobb et al. (2018)

CONSISTENCY INDICES

Plastic index:

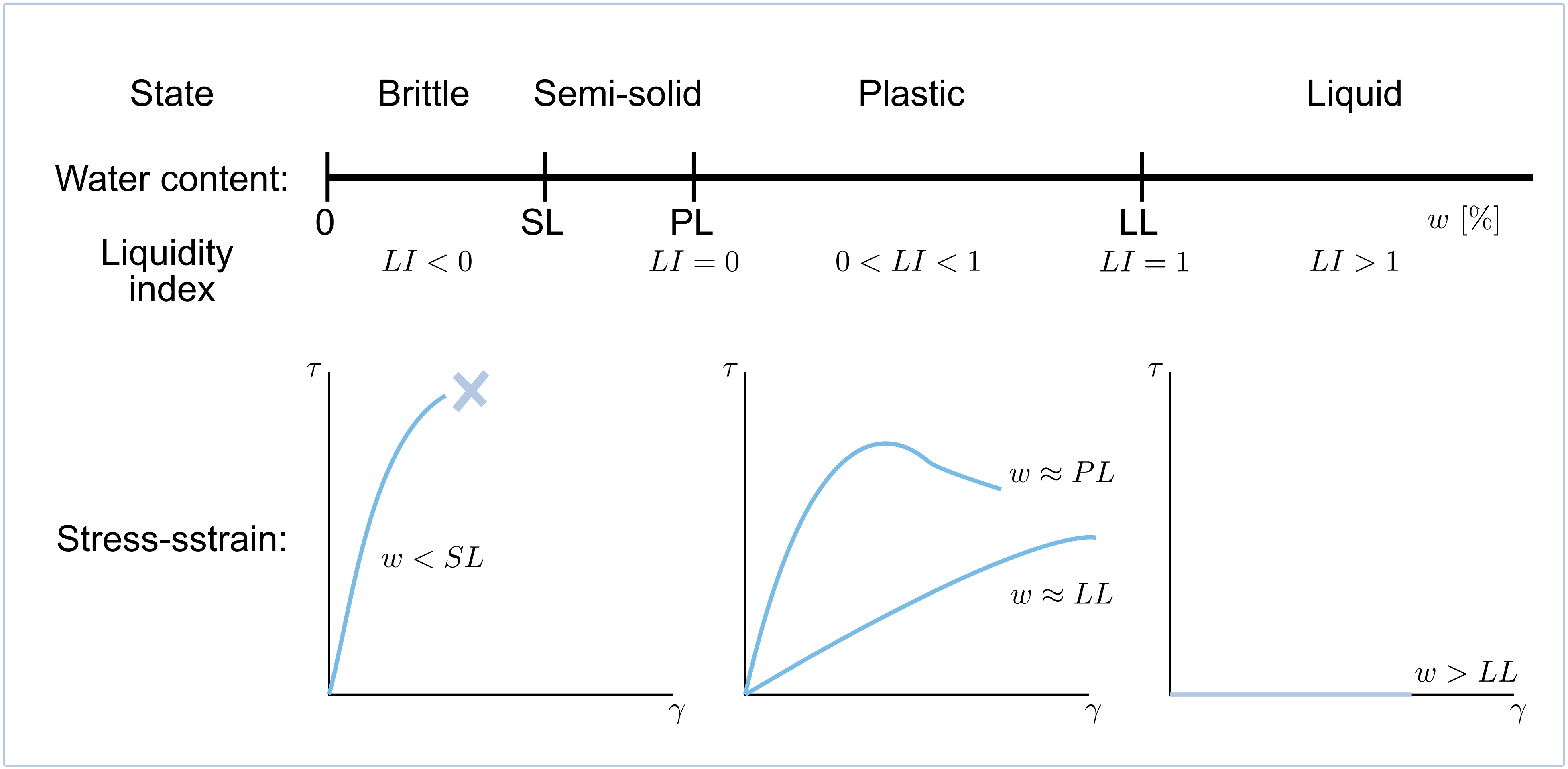
Is the range of water content in which the fine fraction of soils behaves as a plastic material.

$$PI = LL - PL$$

Liquidity index:

This is a scaling parameter that maps the natural water content to the consistency limits.

$$LI = \frac{w_n - PL}{PI}$$



State
Brittle
Semi-solid
Plastic
Liquid
Water content:
0
SL
PL
LL
w [%]
Liquidity index
$LI < 0$
$LI = 0$
$0 < LI < 1$
$LI = 1$
$LI > 1$
Stress-sstrain:
τ
γ
$w < SL$
$w \approx PL$
$w \approx LL$
$w > LL$

ACTIVITY OF CLAYS

Relates the plasticity index and the clay fraction of soils.

$$A = \frac{PI}{C_F}$$

A is highly correlated to clay mineralogy.

Mineral	Activity
Na-montmorillonite	4-7
Ca-montmorillonite	1.5
Illite	0.5-1.3
Kaolinite	0.3-0.5
Hallosyte (dehydrated)	0.5
Hallosyte (hydrated)	0.1
Attapulgite	0.5-1.2
Allophane	0.5-1.2
Mica (muscovite)	0.2
Calcite	0.2
Quartz	0

EXAMPLE 2.7

For the parameters shown in the table, compute LL, PI, LI, and A.

LL results.

Blow count N	$w\%$
55	23.5
43	27.9
22	36.4
15	45.3

- $PL = 12\%$
- $C_F = 13\%$
- $w_n = 38\%$

SOIL CLASSIFICATION

Unified soil classification system (USCS) ASTM D2487.

Input parameters:

- Soil fractions (G_F, S_F, F_F).
- Coefficient of uniformity (C_u).
- Coefficient of gradation or curvature (C_c).
- Liquid limit (LL).
- Plastic index (PI).
- Plasticity chart.

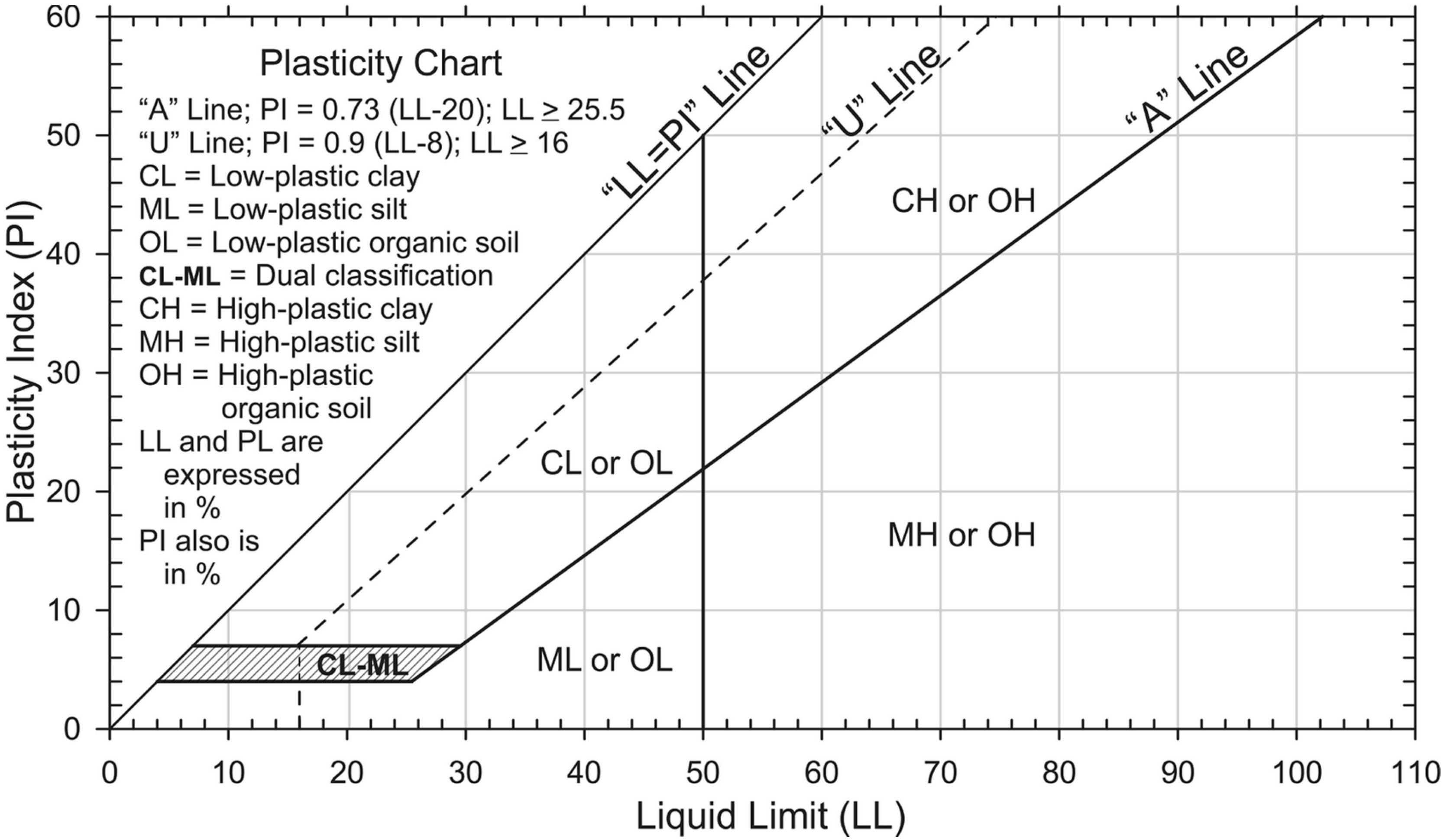
Output:

- Group symbol.
- Group name.

GROUP SYMBOLS

- Two letters
  - First letter $\longrightarrow$ dominant fraction.
  - Second letter $\longrightarrow$ minor fraction
- Dominant fraction
  - Coarse (retained in sieve No 200).
    - Gravel (G), sand (S).
  - Fines (passing sieve No 200).
    - Silt (M), clay (C), organic content (O).
- Minor fraciton
  - Coarse, depending on well/poorly-graded (W, P) and fines (M, C).
  - Fine, depending on low/high plasticity (L,H).

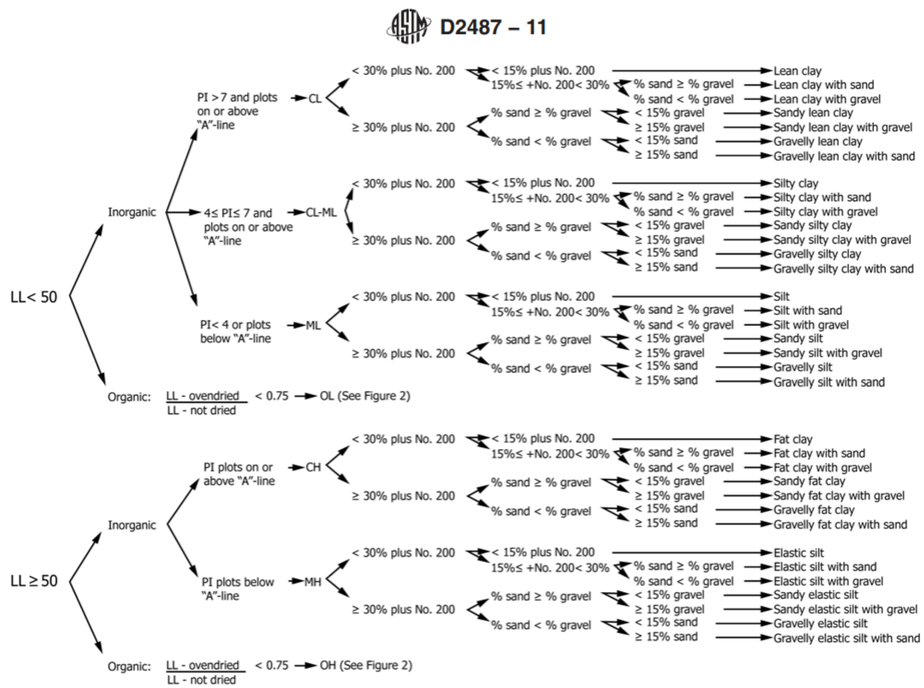
PLASTICITY CHART



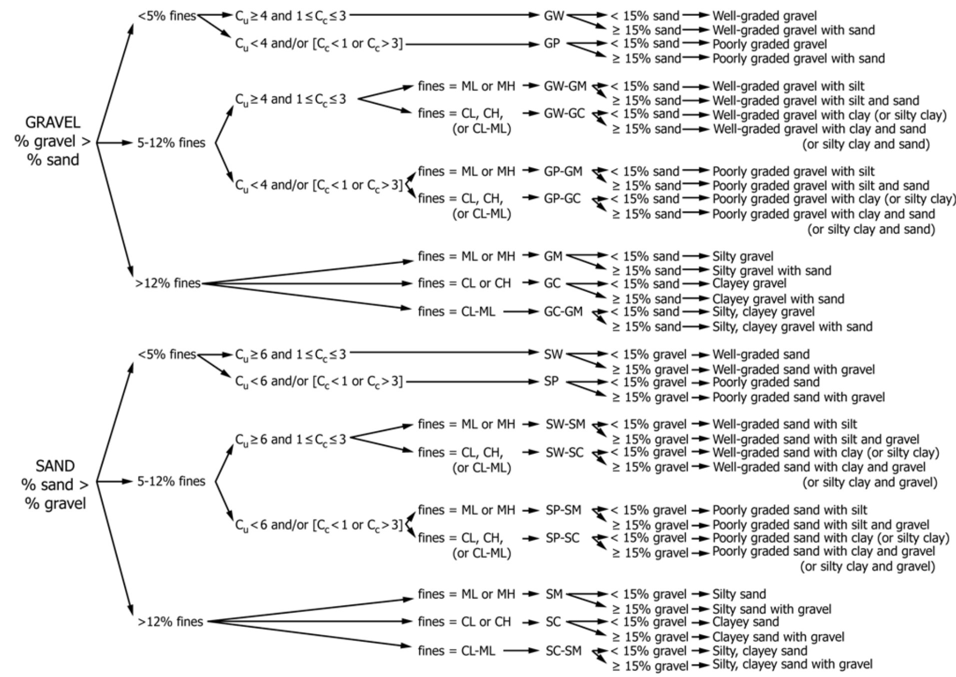
Keaton (2018)

CLASSIFICATION FLOW DIAGRAM

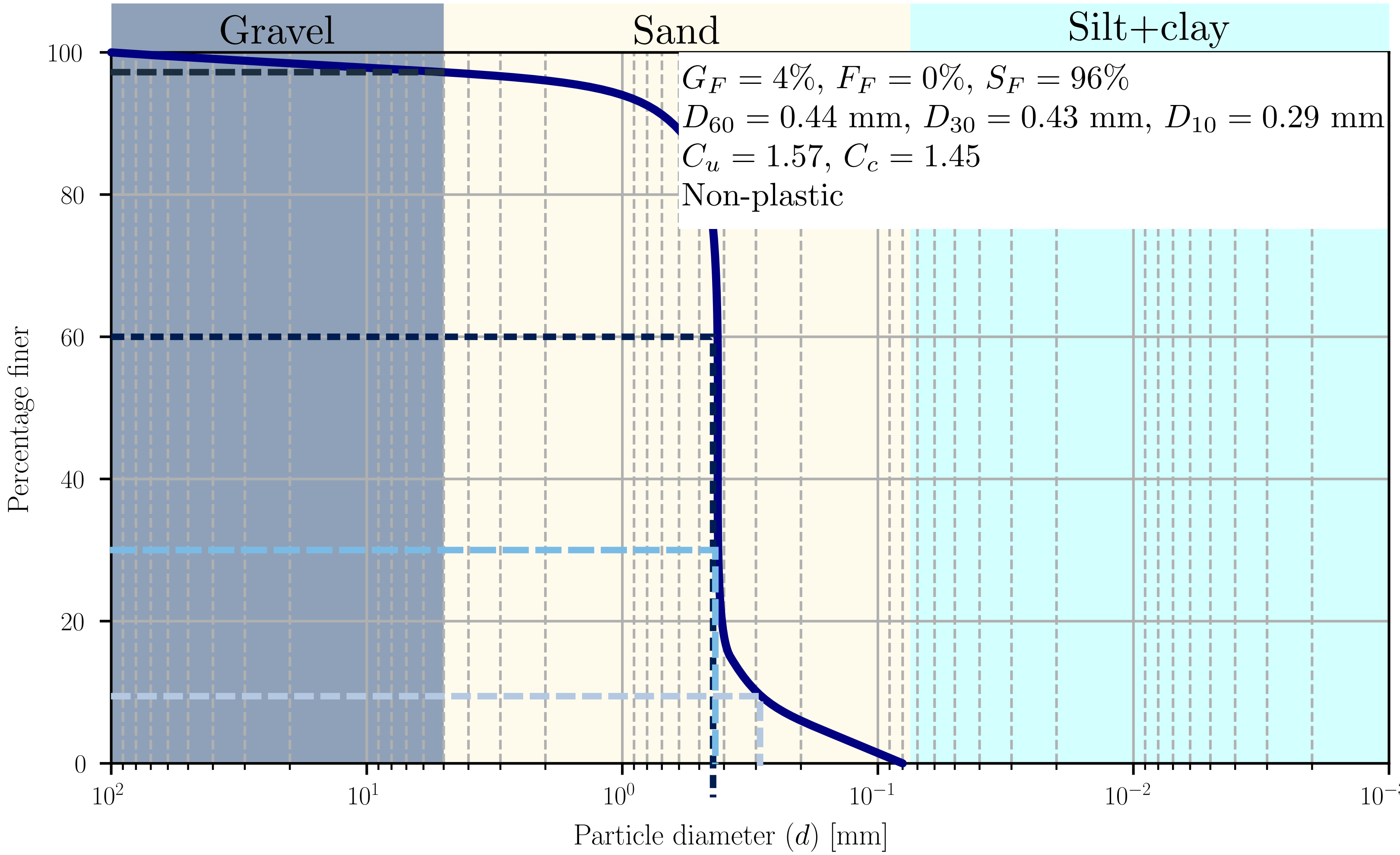
If $F_F \geq 50\%$



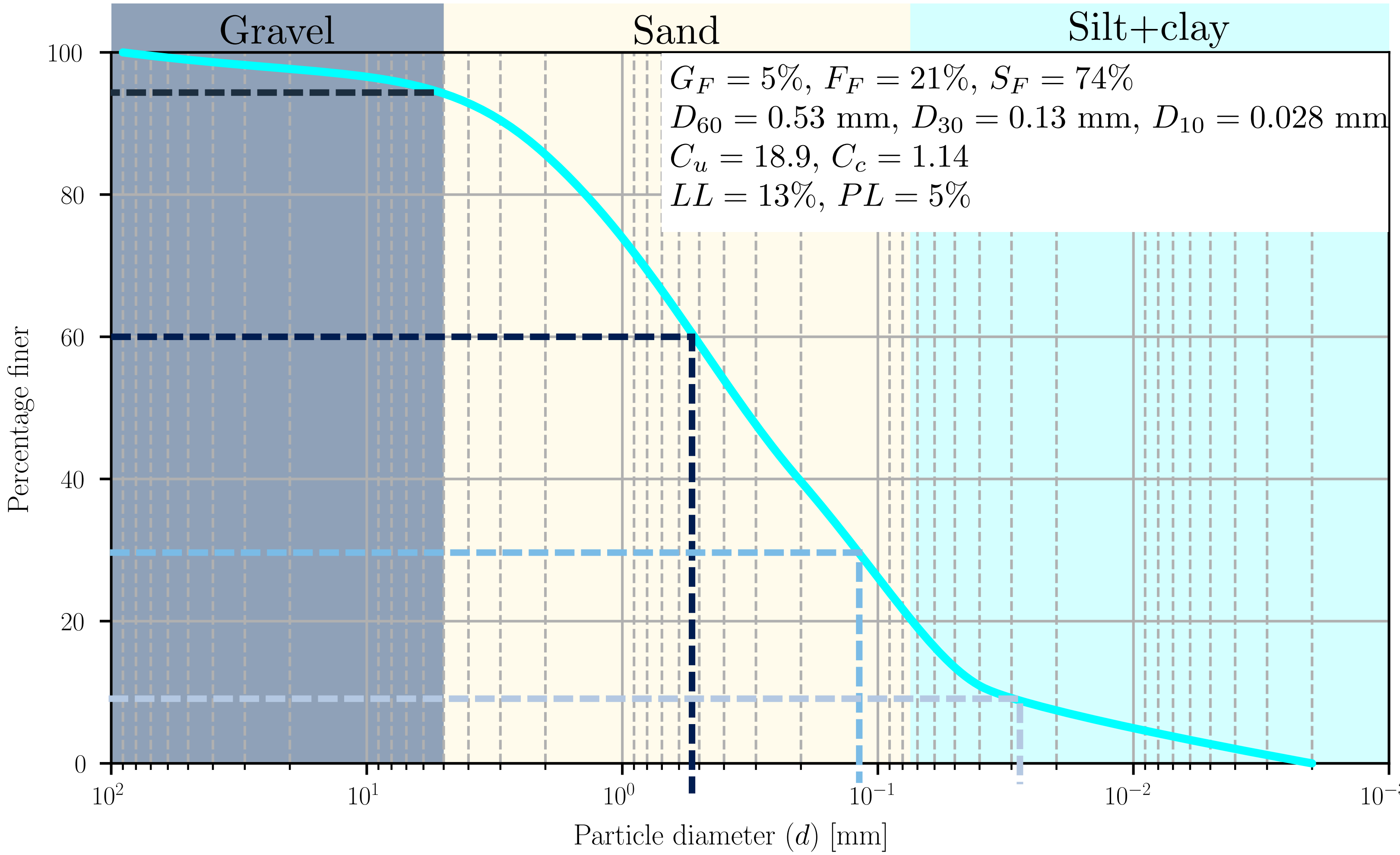
If $F_F < 50\%$



EXAMPLE 2.8

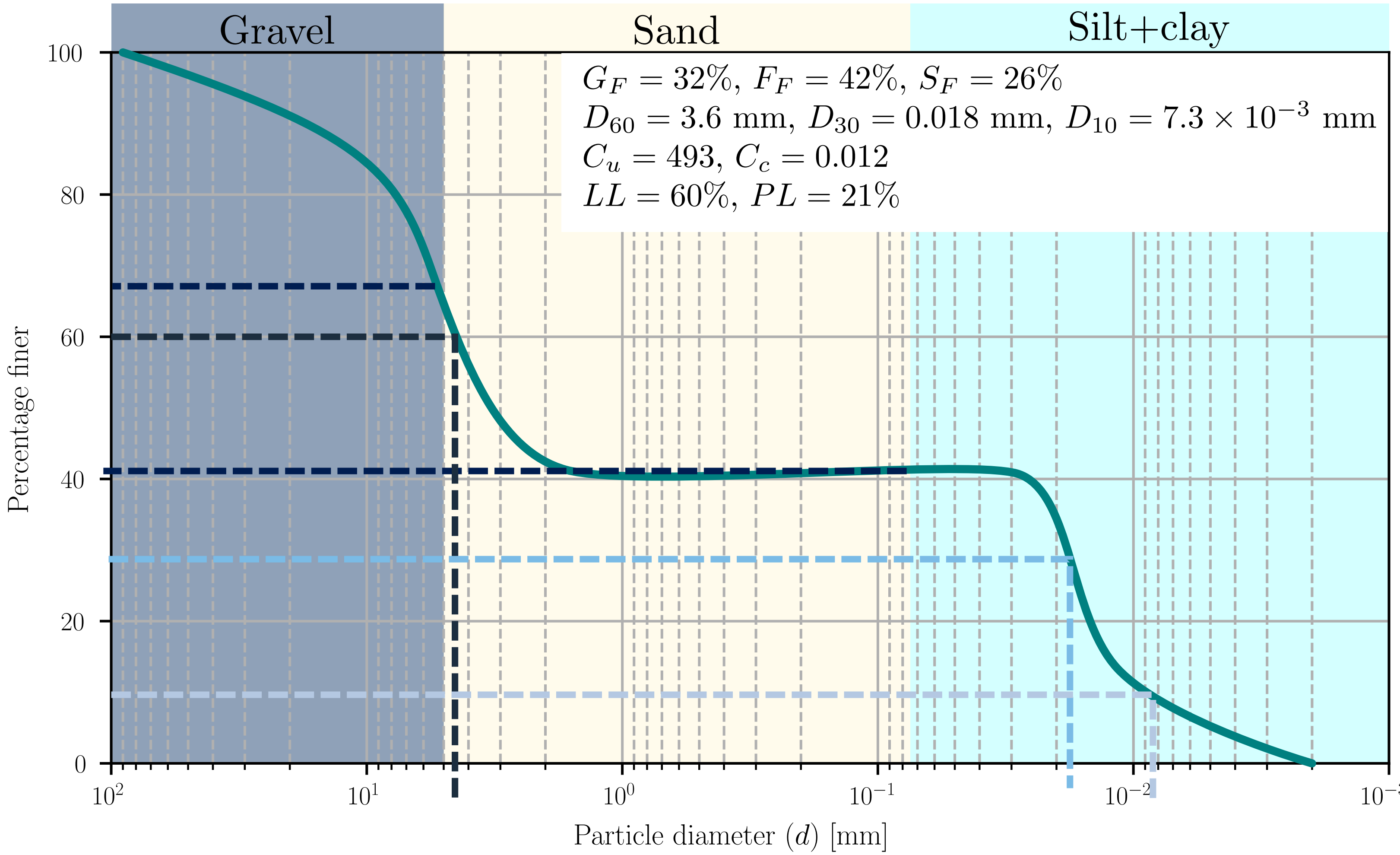

Gravel
Sand
Silt+clay
$G_F = 4\%$, $F_F = 0\%$, $S_F = 96\%$
$D_{60} = 0.44$ mm, $D_{30} = 0.43$ mm, $D_{10} = 0.29$ mm
$C_u = 1.57$, $C_c = 1.45$
Non-plastic
Percentage finer
Particle diameter (d) [mm]
0
20
40
60
80
100
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}

EXAMPLE 2.9



Gravel
Sand
Silt+clay
$G_F = 5\%$, $F_F = 21\%$, $S_F = 74\%$
$D_{60} = 0.53$ mm, $D_{30} = 0.13$ mm, $D_{10} = 0.028$ mm
$C_u = 18.9$, $C_c = 1.14$
$LL = 13\%$, $PL = 5\%$
Percentage finer
0
20
40
60
80
100
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
Particle diameter (d) [mm]

EXAMPLE 2.10



Gravel
Sand
Silt+clay
$G_F = 32\%$, $F_F = 42\%$, $S_F = 26\%$
$D_{60} = 3.6$ mm, $D_{30} = 0.018$ mm, $D_{10} = 7.3 \times 10^{-3}$ mm
$C_u = 493$, $C_c = 0.012$
$LL = 60\%$, $PL = 21\%$
Percentage finer
100
80
60
40
20
0
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
Particle diameter (d) [mm]