Civil Engineering Department
College of Engineering

Course: Soil and Rock Mechanics
(CE 260)

Lecturer: Dr. Frederick Owusu-Nimo

Index Properties

- Important to characterize soils to be able to assess their engineering properties
    - Bearing Capacity (Shear strength)
    - Compressibility
    - Permeability

- Index property tests are tests developed for characterizing soils quickly
    - Particle size distribution
    - Atterberg limit tests

Particle Size Distribution

Soil type based on Particle Size

Designation	Category	Particle Size (mm)
Boulders		> 200
Cobbles		60 - 200
Gravel	Coarse Medium Fine	20 – 60 6 – 20 2- 6
Sand	Coarse Medium Fine	0.6 – 2 0.2 – 0.6 0.06 – 0.2
Silt	Coarse Medium Fine	0.02 – 0.06 0.006- 0.02 0.002-0.006
Clay	Fine	< 0.002

Soil type based on Particle Size

Boulders > 200mm

Cobbles 60-200mm

Gravels 2-60mm

Importance of PSD

- The distribution of grain sizes affects the engineering properties

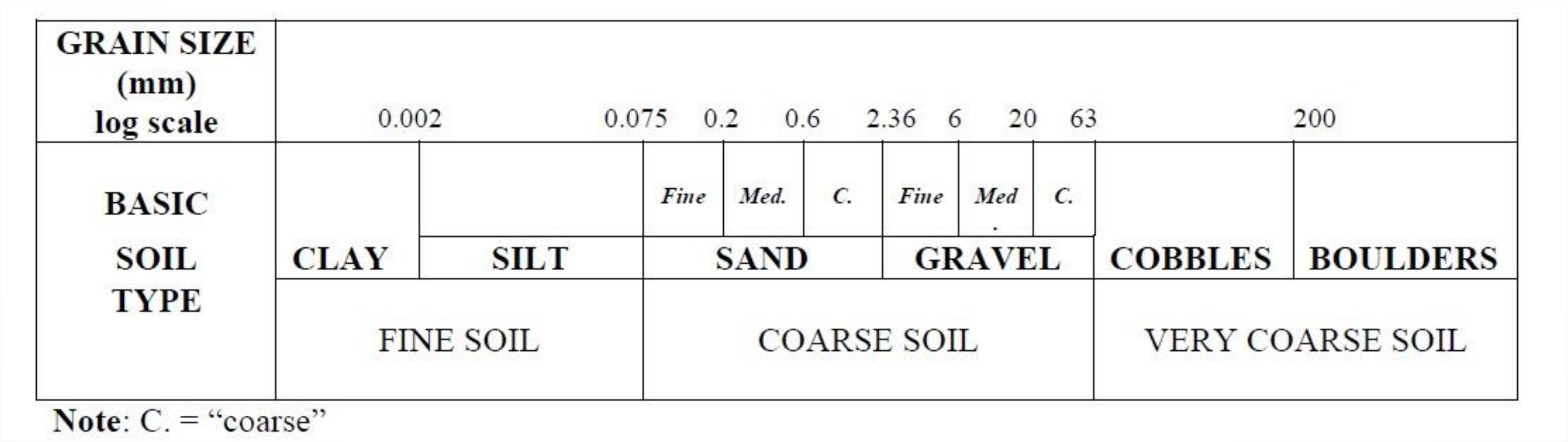
- Example:
    - Soil with mainly one grain size can not be compacted to high density and will therefore have a lower shear strength

    - Soils with grains spanning a wide size distribution can be compacted to a high density resulting in a high shear strength

Determination of PSD

?

Sieve Analysis



GRAIN SIZE (mm) log scale	0.002	0.075	0.2	0.6	2.36	6	20	63	200	
BASIC SOIL TYPE			*Fine*	*Med.*	*C.*	*Fine*	*Med*	*C.*		
	CLAY	SILT	SAND			GRAVEL			COBBLES	BOULDERS
	FINE SOIL		COARSE SOIL						VERY COARSE SOIL	

Note: C. = "coarse"

Sieves commonly used

BS Sieve Designation	ASTM Designation	Aperture
1 in		26.5 mm
¾ in		19.0 mm
½ in	0.53 in	13.2 mm
3/8 in	3/8 in	9.5 mm
¼ in	0.265 in	6.7 mm
3/16 in	No. 4	4.75 mm
No. 7	No. 8	2.36 mm
No. 14	No. 16	1.18 mm
No. 25	No. 30	600 µm
No. 36	No. 40	425 µm
No. 52	No. 50	300 µm
No. 72	No. 70	212 µm
No. 100	No. 100	150 µm
No. 200	No. 200	75 µm

Sieve Analysis (Stack of Sieves)

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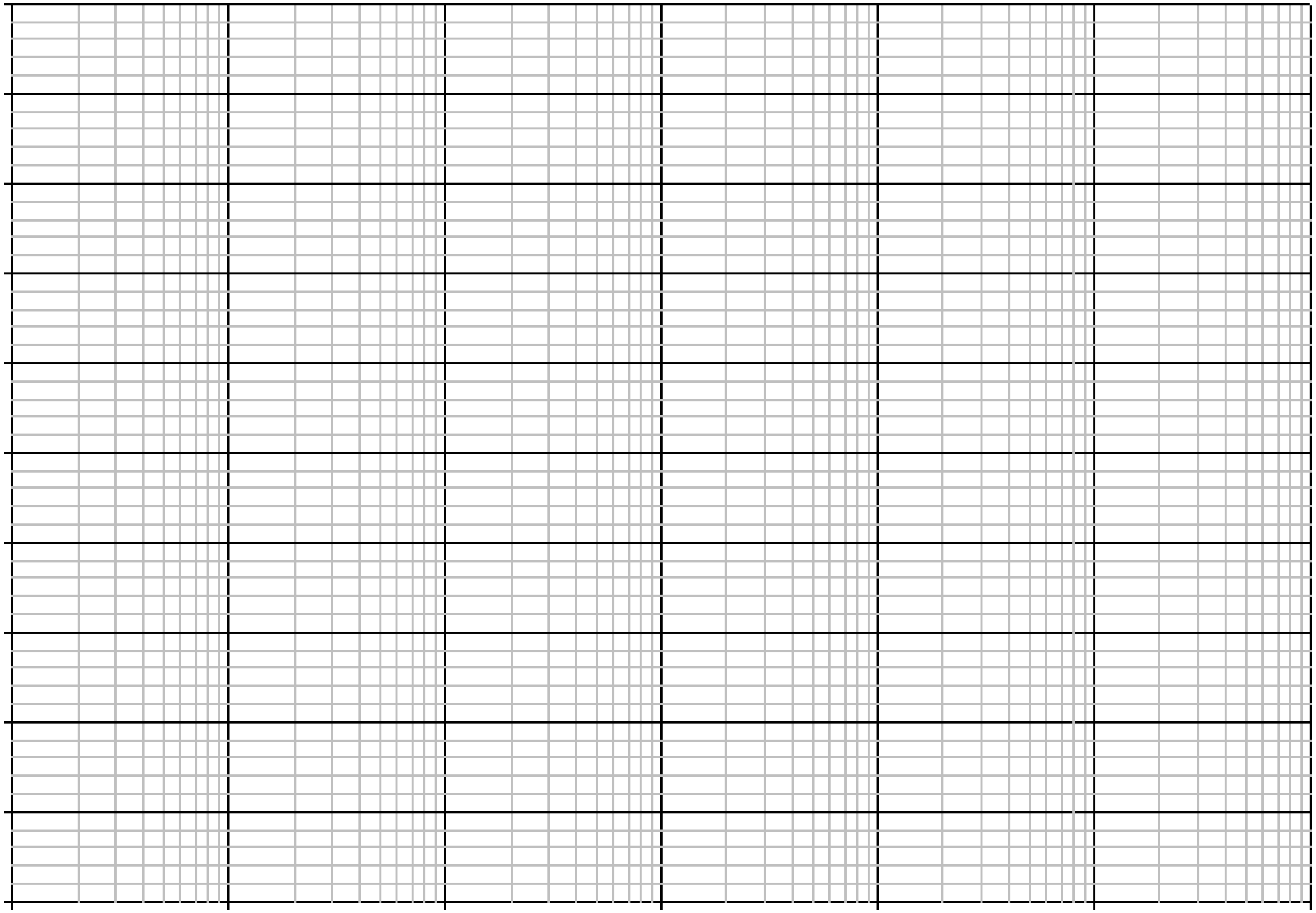
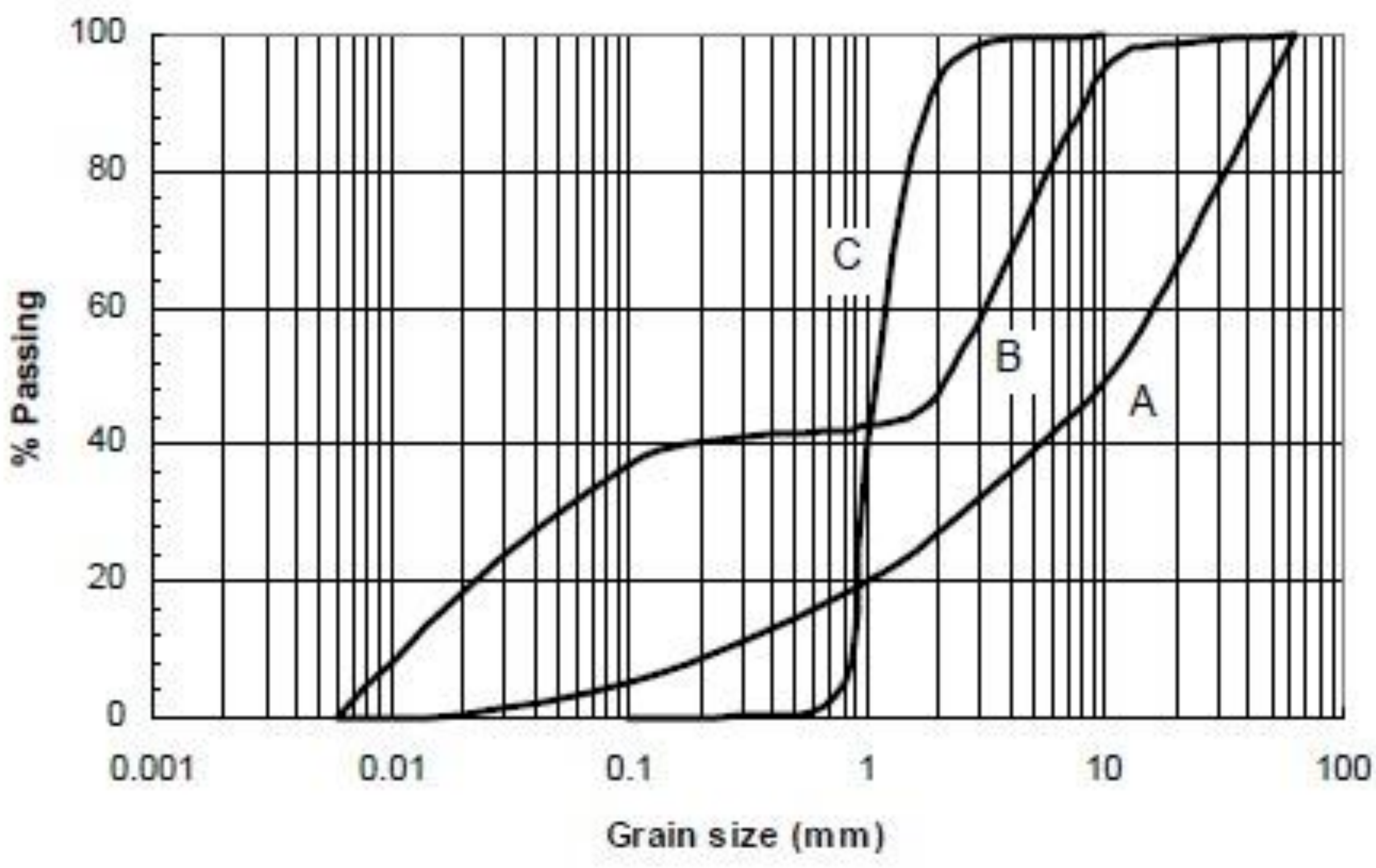
Plotting PSD Curves



Plot % Passing against Grain Size (Sieve Size)

Example of PSD Curves



Worked Example

An air dry soil sample weighing 2000g is brought to the soils lab for mechanical grain size analysis. The lab data are given in the table.

Plot a grain size distribution curve for this sample

US Sieve Analysis	Size Opening (mm)	Weight Retained (g)
¾ in	19.0	0
3/8 in	9.5	158
No. 4	4.75	308
No. 10	2.0	608
N0. 40	0.425	652
No. 100	0.150	224
No. 200	0.075	42
Pan	-	8

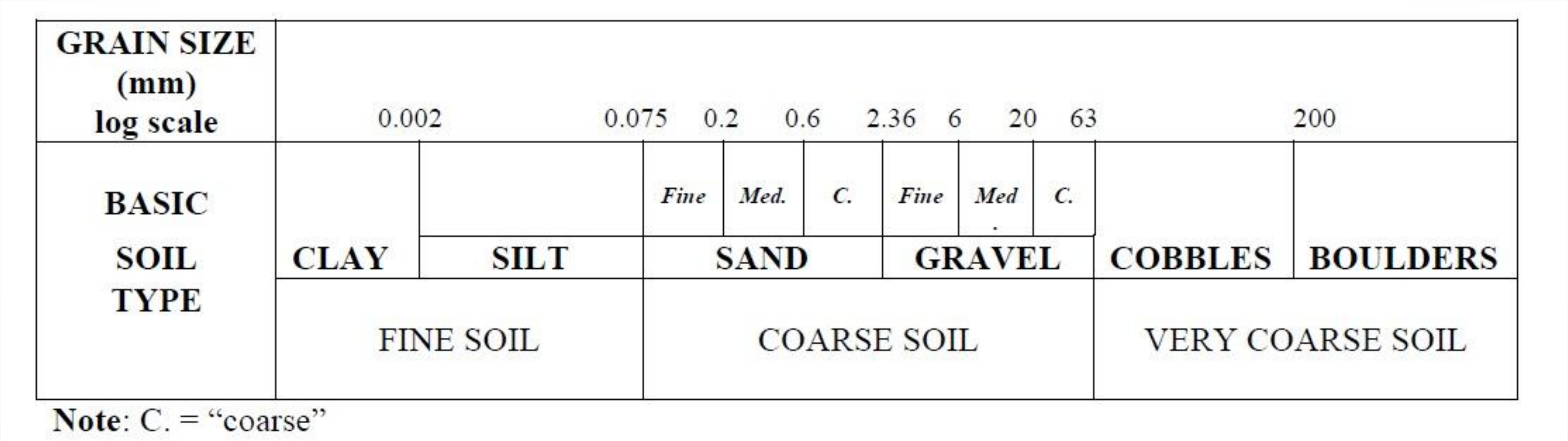
Worked Example

US Sieve Analysis	Size Opening (mm)	Weight Retained (g)	% Retained	Cumulative % Retained	% Passing
¾ in	19.0	0	0	0	100
3/8 in	9.5	158	7.9	7.9	92.1
No. 4	4.75	308	15.4	23.3	76.7
No. 10	2.0	608	30.4	53.7	46.3
N0. 40	0.425	652	32.6	86.3	13.7
No. 100	0.150	224	11.2	97.5	2.5
No. 200	0.075	42	2.1	99.6	0.4
Pan	-	8	0.4	100	-

Determination of PSD


Hydrometer Analysis

Sieve Analysis



GRAIN SIZE (mm) log scale	0.002	0.075	0.2	0.6	2.36	6	20	63	200	
BASIC SOIL TYPE			*Fine*	*Med.*	*C.*	*Fine*	*Med*	*C.*		
	CLAY	**SILT**	**SAND**			**GRAVEL**			**COBBLES**	**BOULDERS**
	FINE SOIL		COARSE SOIL						VERY COARSE SOIL	

Note: C. = "coarse"

Stoke's Law

- Expresses velocity of which a spherical particle falls through a fluid medium as a function of the diameter and specific gravity of the particle

- Limitations of Stoke's law
  - Particles are spherical
  - Flow around particle is laminar

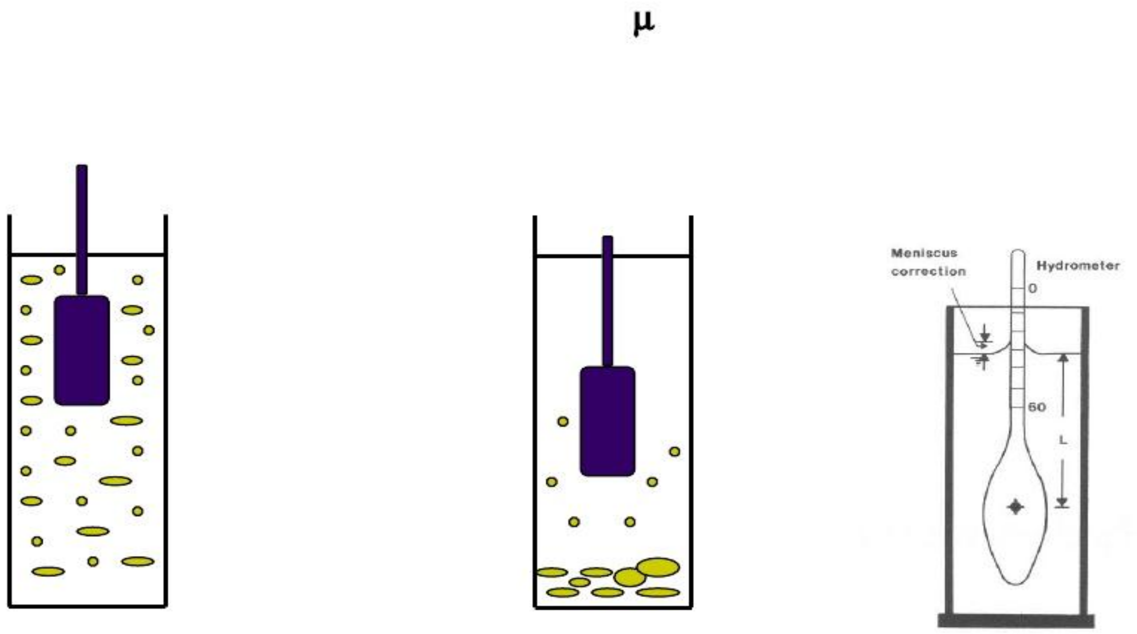
Stoke's Law

- Particles will settle at different velocities based on its size
- After a time t, particles taken at a depth will contain no particle with size larger than "D"
- Therefore density of suspension at any depth is a measure of the quantity of soil smaller than the computed size "D"
- Thus by making density measurements at various times, the particle size distribution can be obtained

Hydrometer Analysis

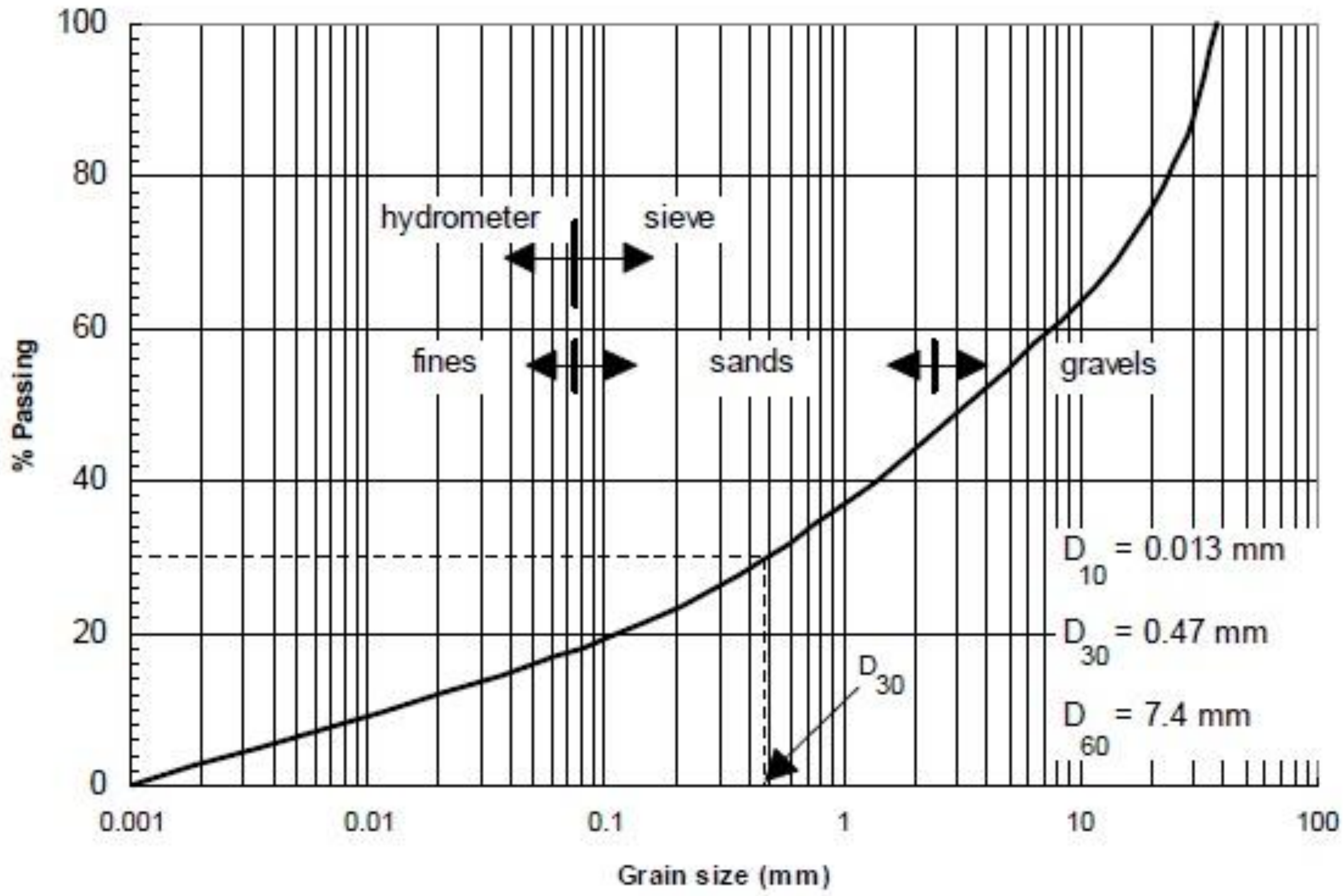
Hydrometer Types Hydrometer Types

Hydrometer Analysis



Denser fluids allow the hydrometer to be more buoyant and float higher

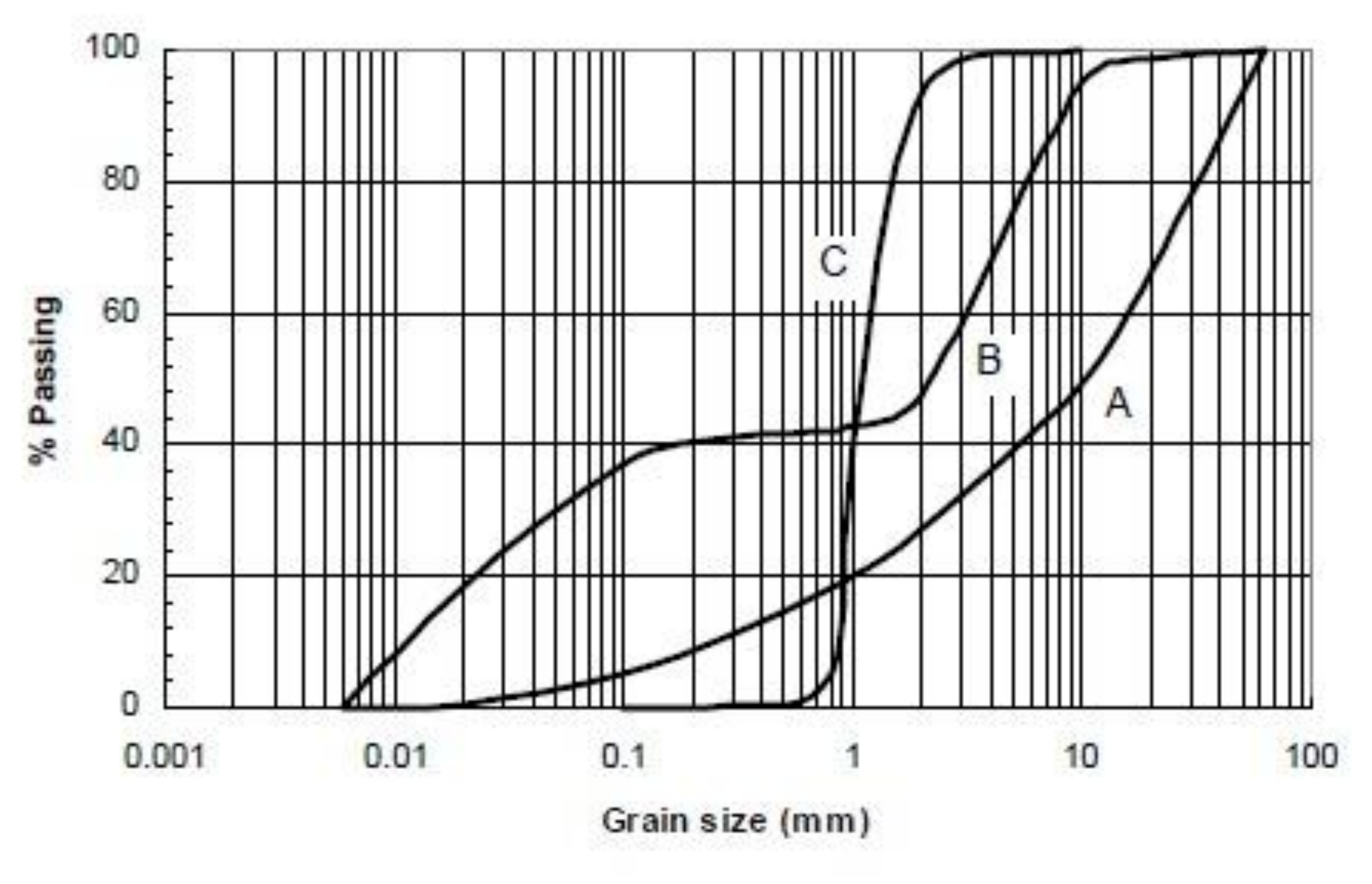
Features of PSD Curve



Features of PSD Curve

- Median Size (D_{50}) – diameter at which 50% of the soil by weight is finer
- Effective Size (D_{10}) - diameter at which 10% of the soil by weight is finer
- Coefficient of Uniformity , Cu; $\mathrm{Cu} = \frac{D_{60}}{D_{10}}$
- Coefficient of Curvature, Cc; $Cc = \frac{D^{2}{}_{30}}{D_{60} \times D_{10}}$

Nature of PSD Curves



Well Graded → Soil A

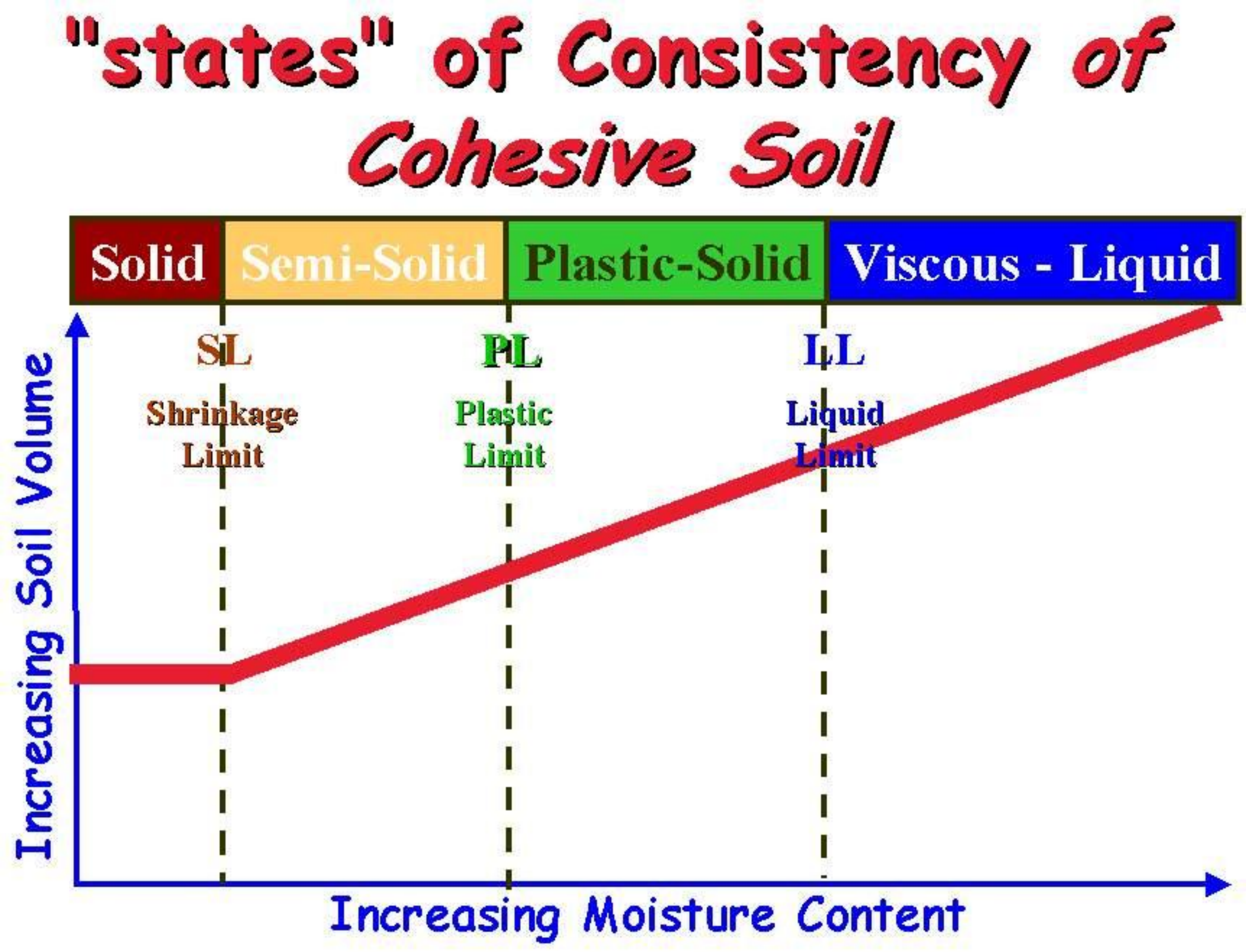
Uniform Graded → Soil C

Gap Graded → Soil B

Soil C, Soil B } Poorly Graded

Atterberg Limits

Atterberg Limits



Atterberg Limits

- **Shrinkage Limit (SL)**: Water content **below** which no further volumetric change takes place as soil is dried
- **Liquid Limit (LL):** Water content **beyond** which soil flows under their own weight (or a specified small force)
- **Plastic Limit (PL):** Water content **at** which plastic deformation can be initiated. Minimum water content at which soil can be rolled into a thread 3mm thick (molded without breaking)
- **Plasticity Index:** Range of water content over which soil remains in plastic condition. PI = LL – PL
- **Liquidity Index (LI):** Indicate nearness of a natural soil to the liquid limit
- **Activity of Clay:** Index for identifying the swelling potential of clay soils. Higher activity implies higher swelling potential.

Atterberg Limits

Typical Values of LL and PL for some common clay minerals

Clay Mineral	Liquid Limit	Plastic Limit	Activity
Kaolinite	35-100	20-40	0.3 – 0.5
Illite	55-120	35-60	0.5 – 1.2
Montmorillonite	100-800	50-100	1.5 – 7.0

Atterberg Limits

Soil Classification System

- A universal language where soils of similar behavior are grouped together, and systematic and rational ways are proposed to classify and describe them.
- Classification based on PSD and Atterberg limits
- Can provide geotechnical engineers a general guidance about engineering properties of the soils through accumulated experience
- Can be used to solve many types of simple foundation problems without need for in depth investigations
- Can be used to guide a test program in case of in depth investigations

Soil Classification System

- Common classification systems for engineering purposes
  - Cassagrande Extended Soil Classification System
  - The Unified Soil Classification System
  - The American Association of State Highway and Transport Officials (AASHTO) Soil Classification System

Cassagrande's Extended Soil Classification System

- Use PSD and Atterberg Limits
- Two main soil groups: Coarse grained and fine grained
- Soils classified using two letters (Prefix and Suffix)

- Prefix –based on predominant particle size
  - G: Gravel
  - S: Sand
  - M: Silt
  - C: Clay
  - O: Organic

- Suffix – related to the engineering properties
  - W: Well-graded
  - P: Poorly-graded
  - H: High plasticity (LL>50%)
  - L: Low plasticity (LL<35%)
- e.g. : GW, SP, CH

GW = Well graded gravels

Cassagrande's Extended Soil Classification System

For Coarse Grained Soils (< 50% fines)

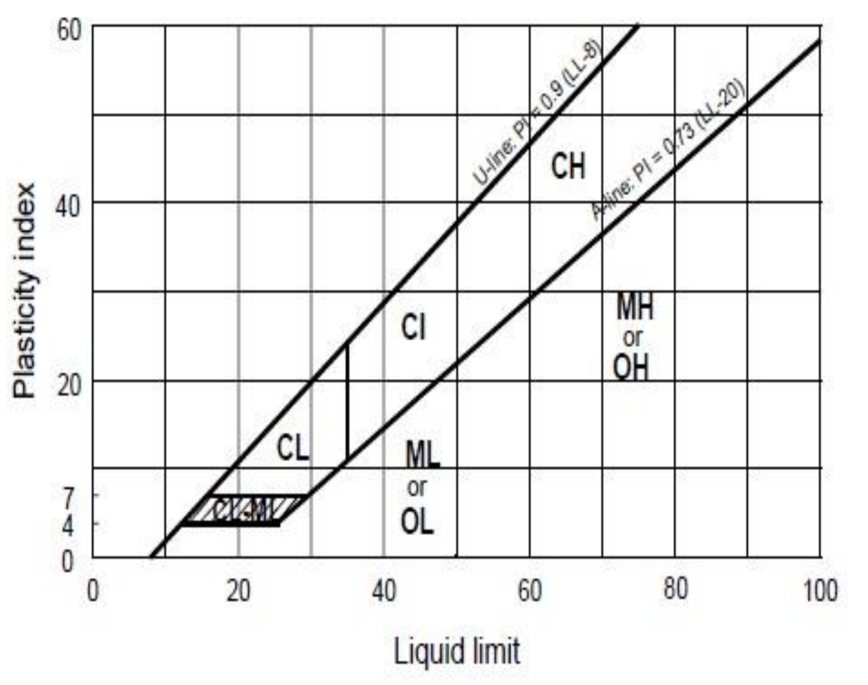
- Prefix
    - G: Gravel (predominant size > 2mm)
    - S: Sand (predominant size < 2mm)
- e.g. : GW, GP, SP, SF

- Suffix
    - W: Well-graded
    - U: Uniform material
    - P: Poorly-graded
    - C: Well graded with some clay
    - F: Well graded with excess of fines

Cassagrande's Extended Soil Classification System

For Fine Grained Soils (> 50% fines)

- Prefix
  - C: Inorganic Clay (Plasticity above A line)
  - M: Silt (Plasticity below A line)
  - O: Organic Clays(Plasticity below A line)
- Suffix
  - H: High Plasticity(LL>50%)
  - I : Intermediate Plasticity (35%<LL<50%)
  - L: Low Plasticity(LL<35%)



- e.g. : CH, ML, CL

Unified Soil Classification System

- Similar to the Cassagrande's Classification System
- Uses grain size distribution and Atterberg limits for classification
- Commonly used for engineering projects
- Soils are grouped into
    - Coarse grained
    - Fine grained
    - Highly Organic Soils

Unified Soil Classification System

50 %

Coarse-grained soils: Fine-grained soils:

Gravel Sand Silt Clay

>50% ***NO. 4***

4.75 mm

NO.200

0.075 mm

- Grain size distribution
- C_u
- C_c

- PL, LL
- Plasticity chart

Unified Soil Classification System

- **Soil symbols:**
- G: Gravel
- S: Sand
- M: Silt
- C: Clay
- O: Organic Clay
- Pt: Peat

Example: SW, Well-graded sand

SC, Clayey sand

SM, Silty sand

- **Liquid limit symbols:**
- H: High Plasticity (LL>50)
- L: Low Plasticity (LL<50)
- **Gradation symbols:**
- W: Well-graded
- P: Poorly-graded

$$\text{Well}-\text{graded soil}$$

$$1 < C_c < 3 \text{ and } C_u \geq 4$$

$$(\text{for gravels})$$

$$1 < C_c < 3 \text{ and } C_u \geq 6$$

$$(\text{for sands})$$

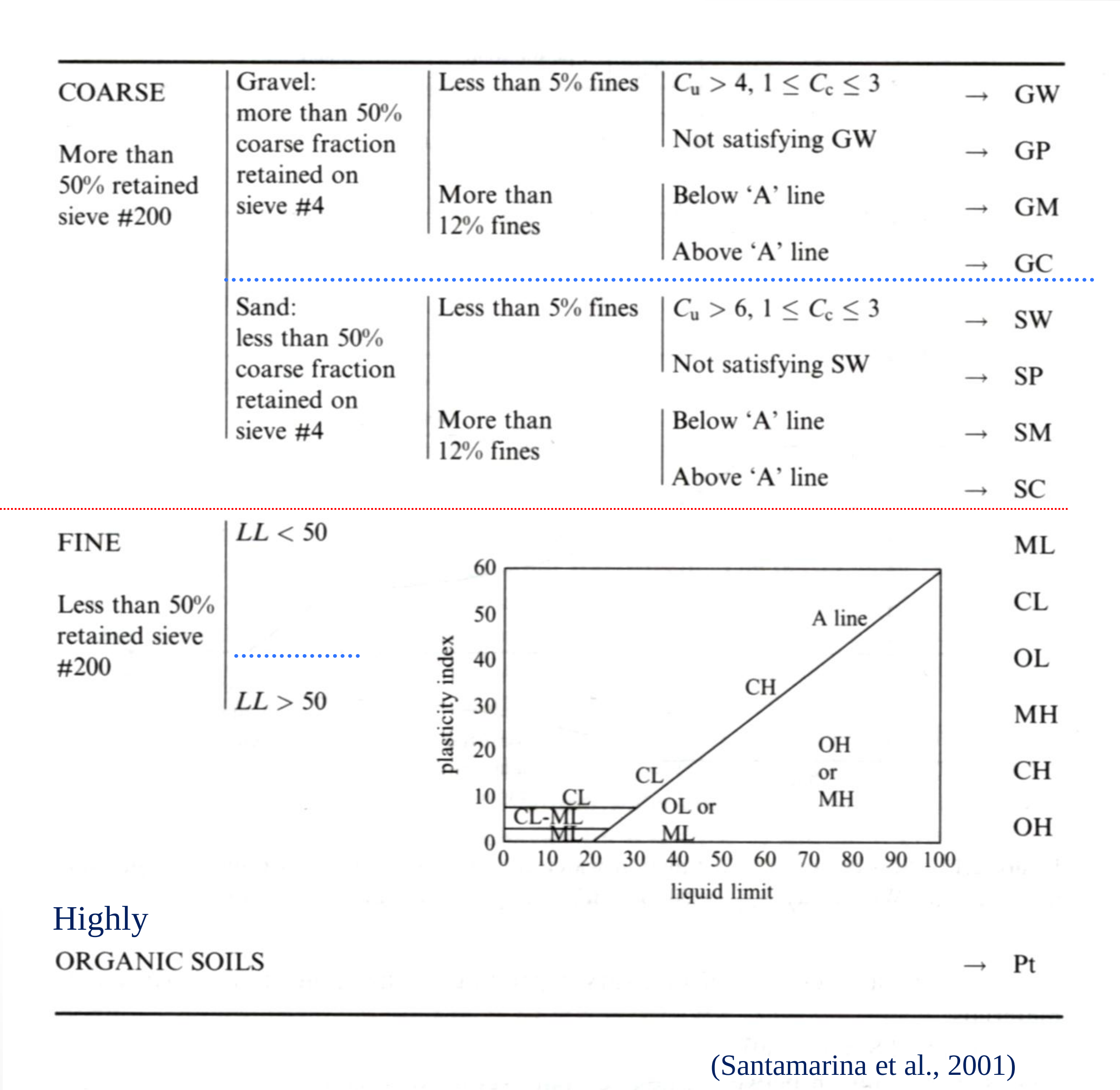
Classification Procedure

Coarse-grained material

Grain size distribution

Fine-grained material

LL, PI



COARSE More than 50% retained sieve #200	Gravel: more than 50% coarse fraction retained on sieve #4	Less than 5% fines	$C_u > 4, 1 \le C_c \le 3$	→ GW
			Not satisfying GW	→ GP
		More than 12% fines	Below 'A' line	→ GM
			Above 'A' line	→ GC
	Sand: less than 50% coarse fraction retained on sieve #4	Less than 5% fines	$C_u > 6, 1 \le C_c \le 3$	→ SW
			Not satisfying SW	→ SP
		More than 12% fines	Below 'A' line	→ SM
			Above 'A' line	→ SC
FINE Less than 50% retained sieve #200	$LL < 50$			ML CL OL
	$LL > 50$			MH CH OH
Highly ORGANIC SOILS				→ Pt

(Santamarina et al., 2001)

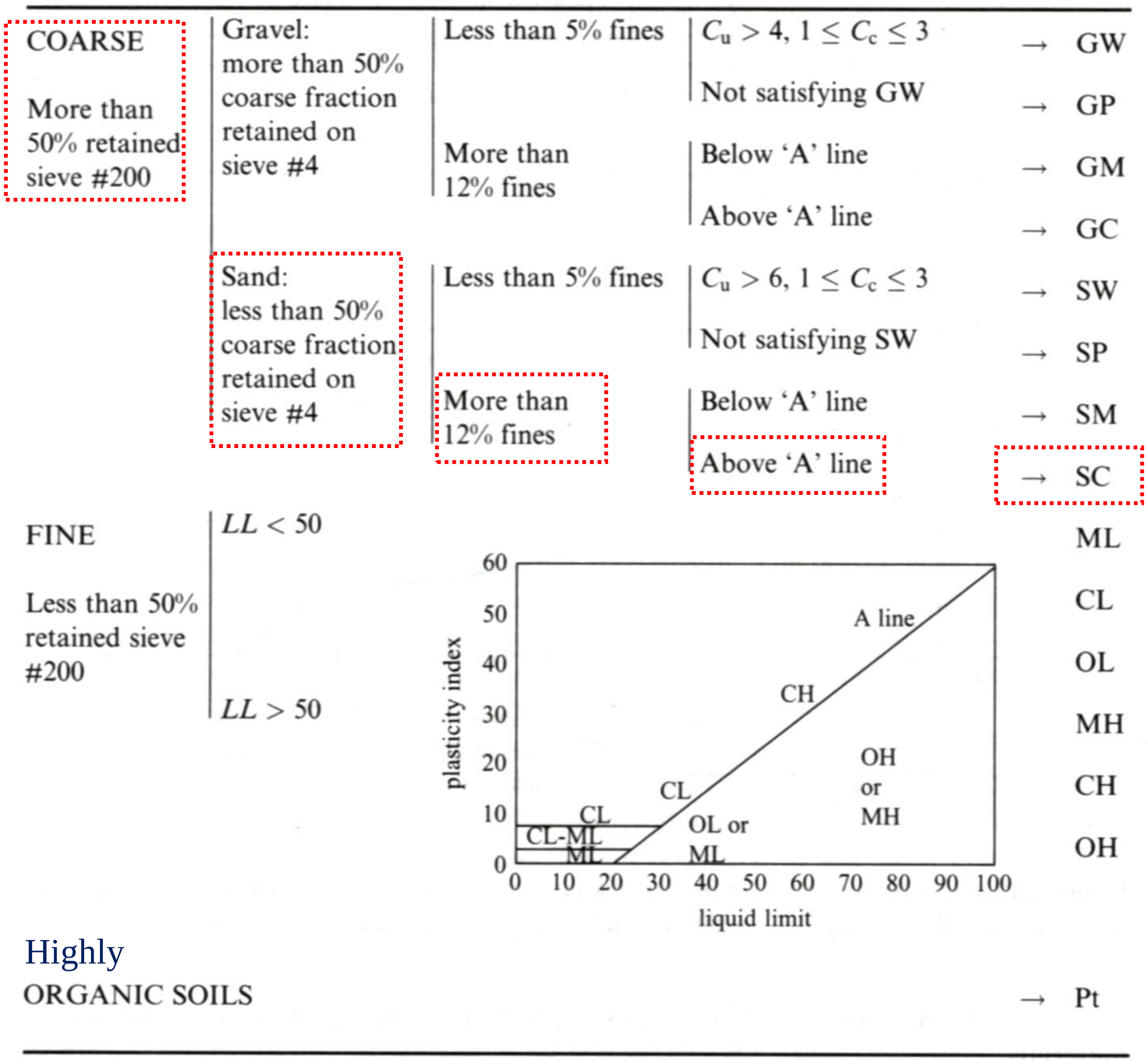
Example

Passing No.200 sieve 30 %

Passing No.4 sieve 70 %

LL= 33%

PI= 12%



COARSE More than 50% retained sieve #200	Gravel: more than 50% coarse fraction retained on sieve #4	Less than 5% fines	$C_u > 4,\ 1 \leq C_c \leq 3$	→ GW
			Not satisfying GW	→ GP
		More than 12% fines	Below 'A' line	→ GM
			Above 'A' line	→ GC
	Sand: less than 50% coarse fraction retained on sieve #4	Less than 5% fines	$C_u > 6,\ 1 \leq C_c \leq 3$	→ SW
			Not satisfying SW	→ SP
		More than 12% fines	Below 'A' line	→ SM
			Above 'A' line	→ SC
FINE Less than 50% retained sieve #200	$LL < 50$			ML CL OL
	$LL > 50$			MH CH OH
Highly ORGANIC SOILS				→ Pt

Passing No.200 sieve 30 %

Passing No.4 sieve 70 %

LL= 33

PI= 12

PI= 0.73(LL-20), A-line

PI=0.73(33-20)=9.49

SC

clayey sand

Example

Passing No.200 sieve 30 %

Passing No.4 sieve 60 %

LL= 33%

PI= 12%

Passing No.200 sieve 30 %

Passing No.4 sieve 60 %

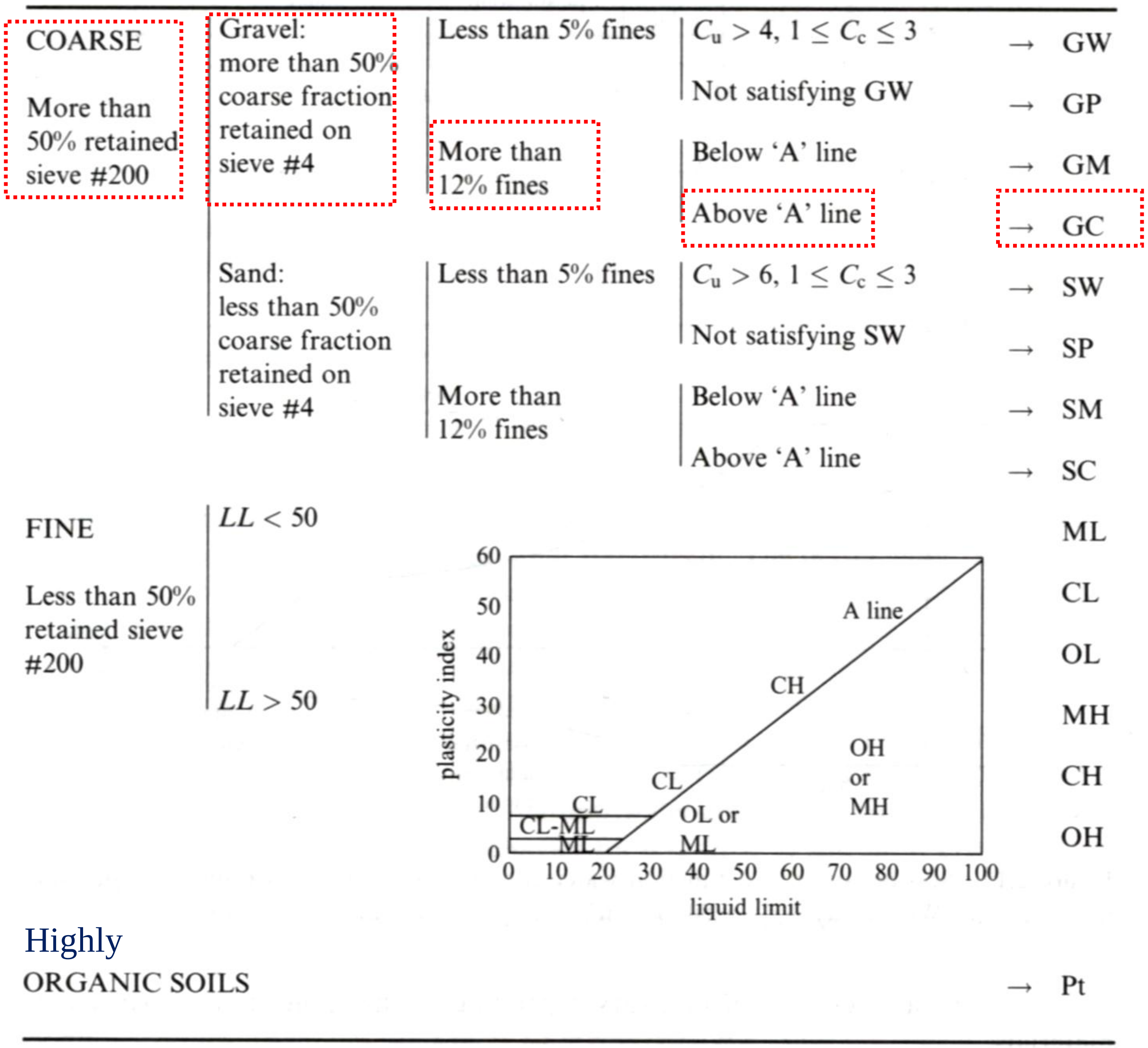
LL= 33

PI= 12

PI= 0.73(LL-20), A-line

PI=0.73(33-20)=9.49

GC
Clayey gravel



COARSE More than 50% retained sieve #200	Gravel: more than 50% coarse fraction retained on sieve #4	Less than 5% fines	$C_u > 4$, $1 \le C_c \le 3$	→ GW
			Not satisfying GW	→ GP
		More than 12% fines	Below 'A' line	→ GM
			Above 'A' line	→ GC
	Sand: less than 50% coarse fraction retained on sieve #4	Less than 5% fines	$C_u > 6$, $1 \le C_c \le 3$	→ SW
			Not satisfying SW	→ SP
		More than 12% fines	Below 'A' line	→ SM
			Above 'A' line	→ SC
FINE Less than 50% retained sieve #200	$LL < 50$			ML
				CL
				OL
	$LL > 50$			MH
				CH
				OH
Highly ORGANIC SOILS				→ Pt

Home Work

- Results of Lab tests is as follows
    - LL = 42.3%
    - PL= 15.8%

Sieve Number	Percentage Passing
No. 4	100
No. 10	93.2
No. 40	81.0
No. 200	60.2

- Classify the soil using the Unified Soil Classification system

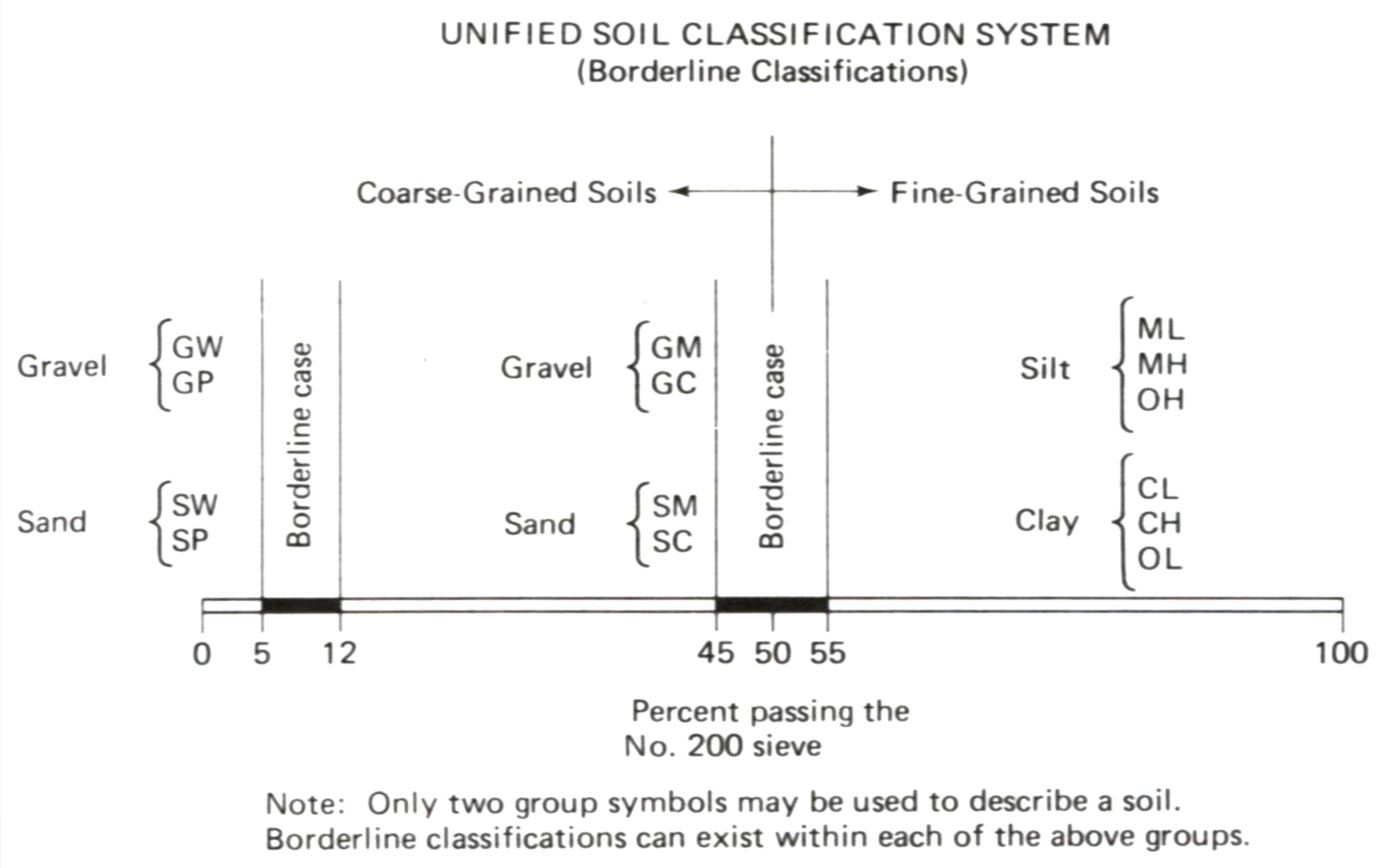
Organic Soils

- **Highly organic soils- Peat (Group symbol Pt)**
  - A sample composed primarily of vegetable tissue in various stages of decomposition, a dark-brown to black color, and an organic odor should be designated as a highly organic soil and shall be classified as peat, Pt.
- **Organic clay (group symbol OL or OH):**
  - "The soil's liquid limit (LL) after oven drying is less than 75 % of its liquid limit before oven drying." If the above statement is true, then the first symbol is O.
  - The second symbol is obtained by locating the values of PI and LL (not oven dried) in the plasticity chart.

Borderline Cases (Dual Symbols)

- A dual symbol is used for the following conditions
  - Coarse-grained soils with 5% - 12% fines.
    - About 7 % fines can change the hydraulic conductivity of the coarse-grained media by orders of magnitude.
    - The first symbol indicates whether the coarse fraction is well or poorly graded. The second symbol describe the contained fines. For example: SP-SM, poorly graded sand with silt.
  - Fine-grained soils with limits within the shaded zone. (PI between 4 and 7 and LL between about 12 and 25).
    - It is hard to distinguish between the silty and more clay like materials.
    - CL-ML: Silty clay, SC-SM: Silty, clayey sand.
  - Soil contain similar fines and coarse-grained fractions.
    - possible dual symbols GM-ML

Borderline Cases (Summary)



Note: Only two group symbols may be used to describe a soil. Borderline classifications can exist within each of the above groups.

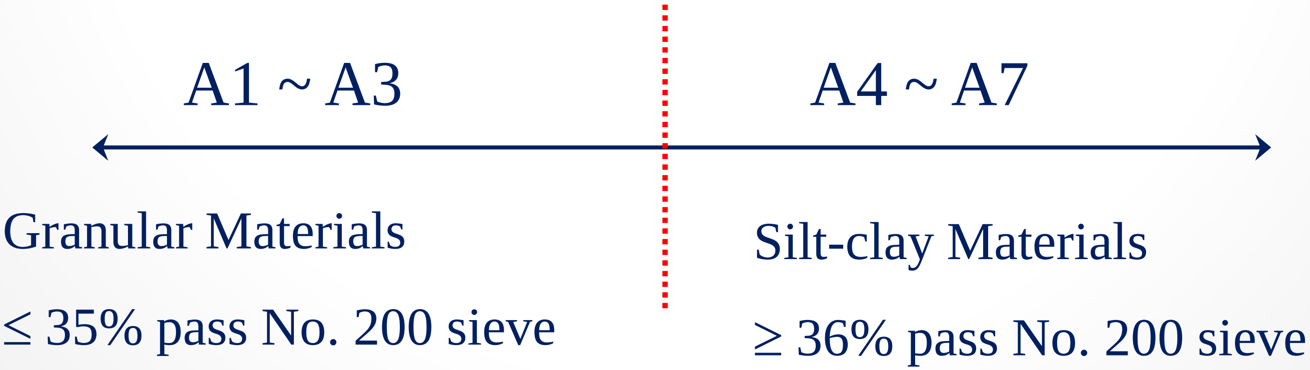
(Holtz and Kovacs, 1981)

Engineering Use Chart

- Embankment and foundation construction
- Roads and Airfields construction

The AASHTO Classification System

- The American Association of State Highway and Transportation Officials system (AASHTO) classification system is widely used for highway (road) work.
- The required parameters are grading curve, liquid limit and plastic limit.
- Soils divided into 8 major groups: A1~ A7 (with several subgroups) and organic soils A8.



A1 ~ A3

A4 ~ A7

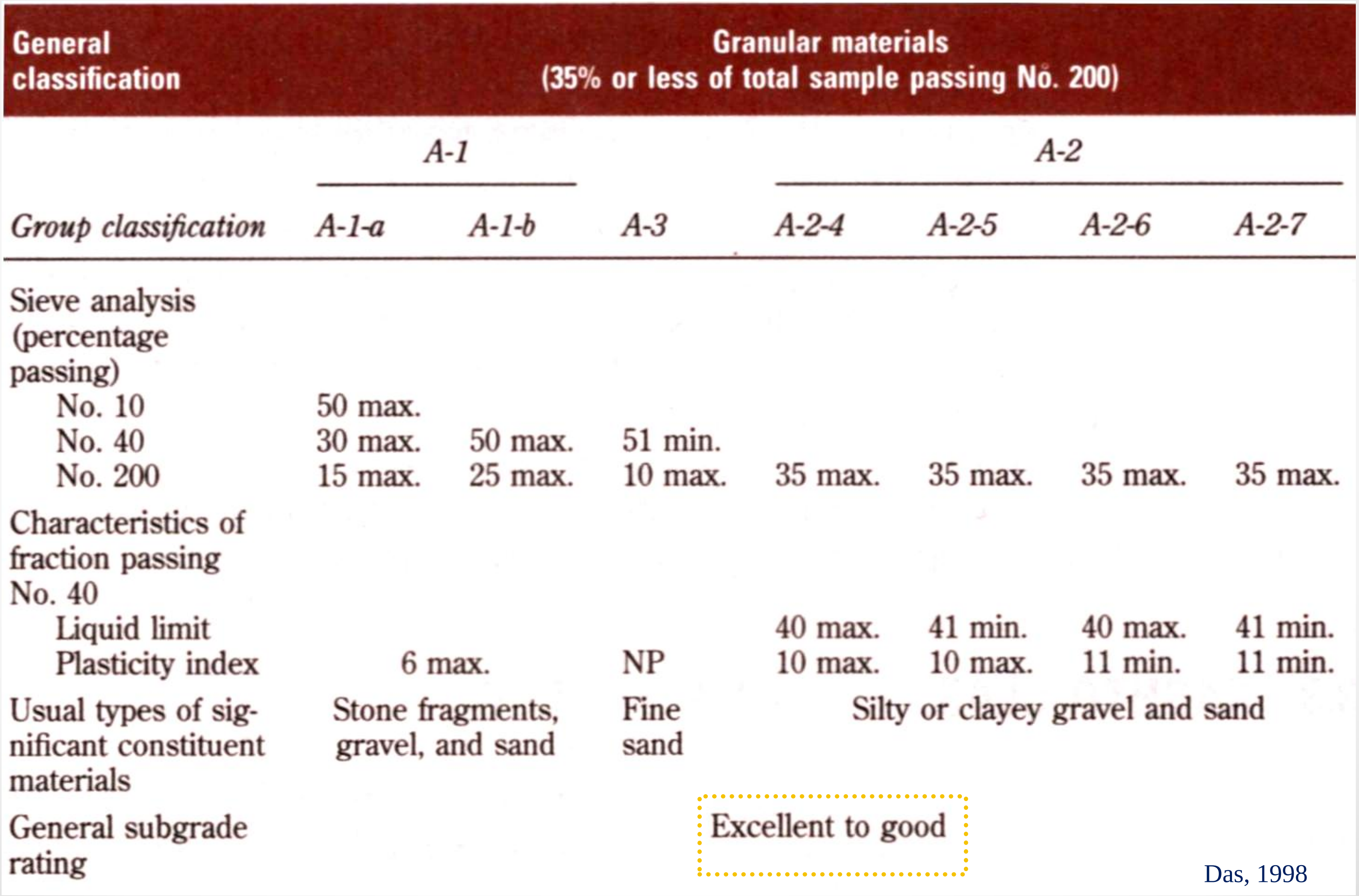
Granular Materials

≤ 35% pass No. 200 sieve

Silt-clay Materials

≥ 36% pass No. 200 sieve

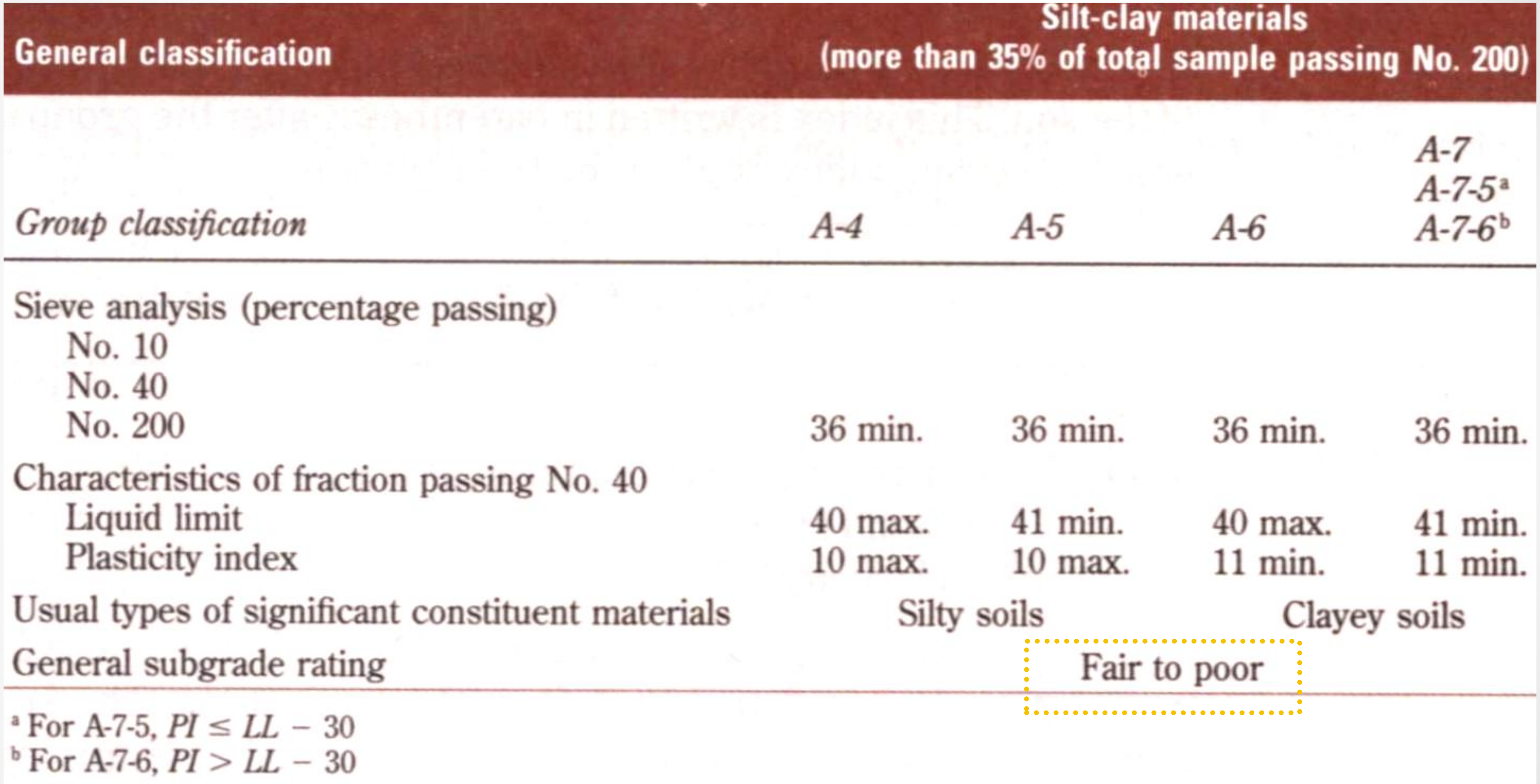
Classification – Granular material



General classification	Granular materials (35% or less of total sample passing No. 200)						
	A-1			A-2			
Group classification	*A-1-a*	*A-1-b*	*A-3*	*A-2-4*	*A-2-5*	*A-2-6*	*A-2-7*
Sieve analysis (percentage passing)							
No. 10	50 max.						
No. 40	30 max.	50 max.	51 min.				
No. 200	15 max.	25 max.	10 max.	35 max.	35 max.	35 max.	35 max.
Characteristics of fraction passing No. 40							
Liquid limit				40 max.	41 min.	40 max.	41 min.
Plasticity index	6 max.		NP	10 max.	10 max.	11 min.	11 min.
Usual types of significant constituent materials	Stone fragments, gravel, and sand		Fine sand	Silty or clayey gravel and sand			
General subgrade rating	Excellent to good						

Das, 1998

Classification- Silt clay material



General classification	Silt-clay materials (more than 35% of total sample passing No. 200)			
Group classification	*A-4*	*A-5*	*A-6*	*A-7* *A-7-5*[a] *A-7-6*[b]
Sieve analysis (percentage passing)				
No. 10				
No. 40				
No. 200	36 min.	36 min.	36 min.	36 min.
Characteristics of fraction passing No. 40				
Liquid limit	40 max.	41 min.	40 max.	41 min.
Plasticity index	10 max.	10 max.	11 min.	11 min.
Usual types of significant constituent materials	Silty soils		Clayey soils	
General subgrade rating	Fair to poor			

[a] For A-7-5, $PI \leq LL - 30$

[b] For A-7-6, $PI > LL - 30$

Note:

The first group from the left to fit the test data is the correct AASHTO classification.

Das, 1998

The AASHTO Classification System

- The group index (GI), an empirical formula, is used to further evaluate soils within a group (subgroups).

The first term is determined by the LL

$$\begin{aligned} \mathrm{GI} &= (\mathrm{F}_{200} - 35)\left[0.2 + 0.005(\mathrm{LL} - 40)\right] \\ &\quad + 0.01(\mathrm{F}_{200} - 15)(\mathrm{PI} - 10) \end{aligned}$$

The second term is determined by the PI

- GI rounded off to the nearest whole number and appended in parenthesis
- If GI = 0 or negative; then GI = 0
- In general, the rating for a pavement subgrade is inversely proportional to the GI (lower the GI, better the material).

Example

% Passing No.200;   86%

LL=70, PI=32

LL-30=40 > PI=32

% Passing No.200 86%

LL=70, PI=32

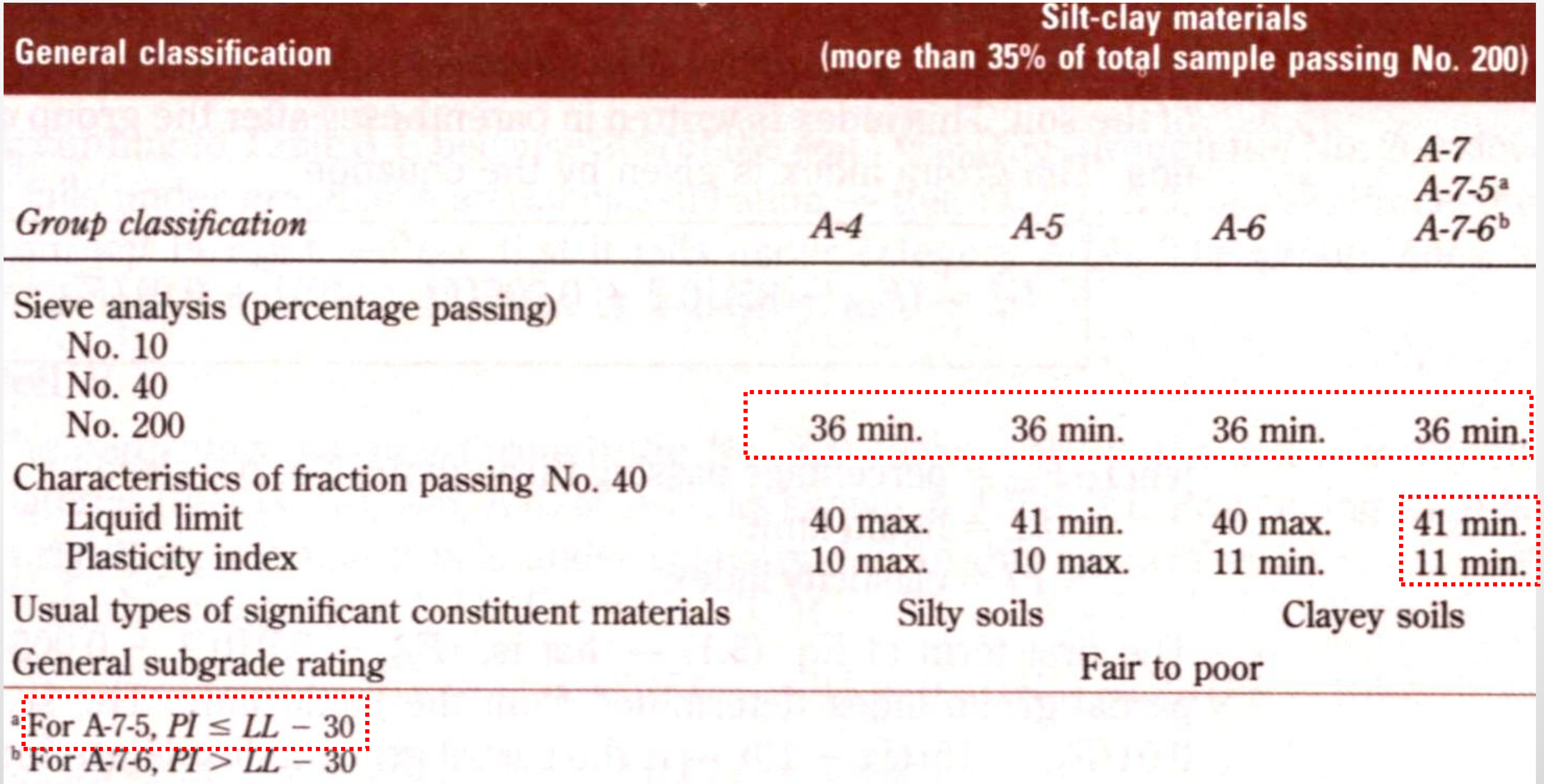
LL-30=70-30=40 > PI=32

$$GI=(F_{200}-35)\left[0.2+0.005(LL-40)\right]$$

$$+0.01(F_{200}-15)(PI-10)$$

$$=33.47\cong 33$$ *Round off*

A-7-5(33)



General classification	Silt-clay materials (more than 35% of total sample passing No. 200)			
Group classification	*A-4*	*A-5*	*A-6*	*A-7* *A-7-5*[a] *A-7-6*[b]
Sieve analysis (percentage passing)				
No. 10				
No. 40				
No. 200	36 min.	36 min.	36 min.	36 min.
Characteristics of fraction passing No. 40				
Liquid limit	40 max.	41 min.	40 max.	41 min.
Plasticity index	10 max.	10 max.	11 min.	11 min.
Usual types of significant constituent materials	Silty soils		Clayey soils	
General subgrade rating	Fair to poor			

[a] For A-7-5, $PI \le LL - 30$

[b] For A-7-6, $PI > LL - 30$