Physical Properties of Soil

Outline

1. Soil Texture
2. Grain Size and Grain Size Distribution
3. Particle Shape
4. Atterberg Limits
5. Some Thoughts about the Sieve Analysis
6. Some Thoughts about the Hydrometer Analysis
7. Suggested works

1. Soil Texture

1.1 Soil Texture

The texture of a soil is its appearance or "**feel**" and it depends on the relative sizes and shapes of the particles as well as the range or distribution of those sizes.

Coarse-grained soils: **Fine-grained soils**:

Gravel Sand Silt Clay

0.075 mm (USCS)

0.06 mm (BS)

Sieve analysis ***Hydrometer analysis***

1.2 Characteristics

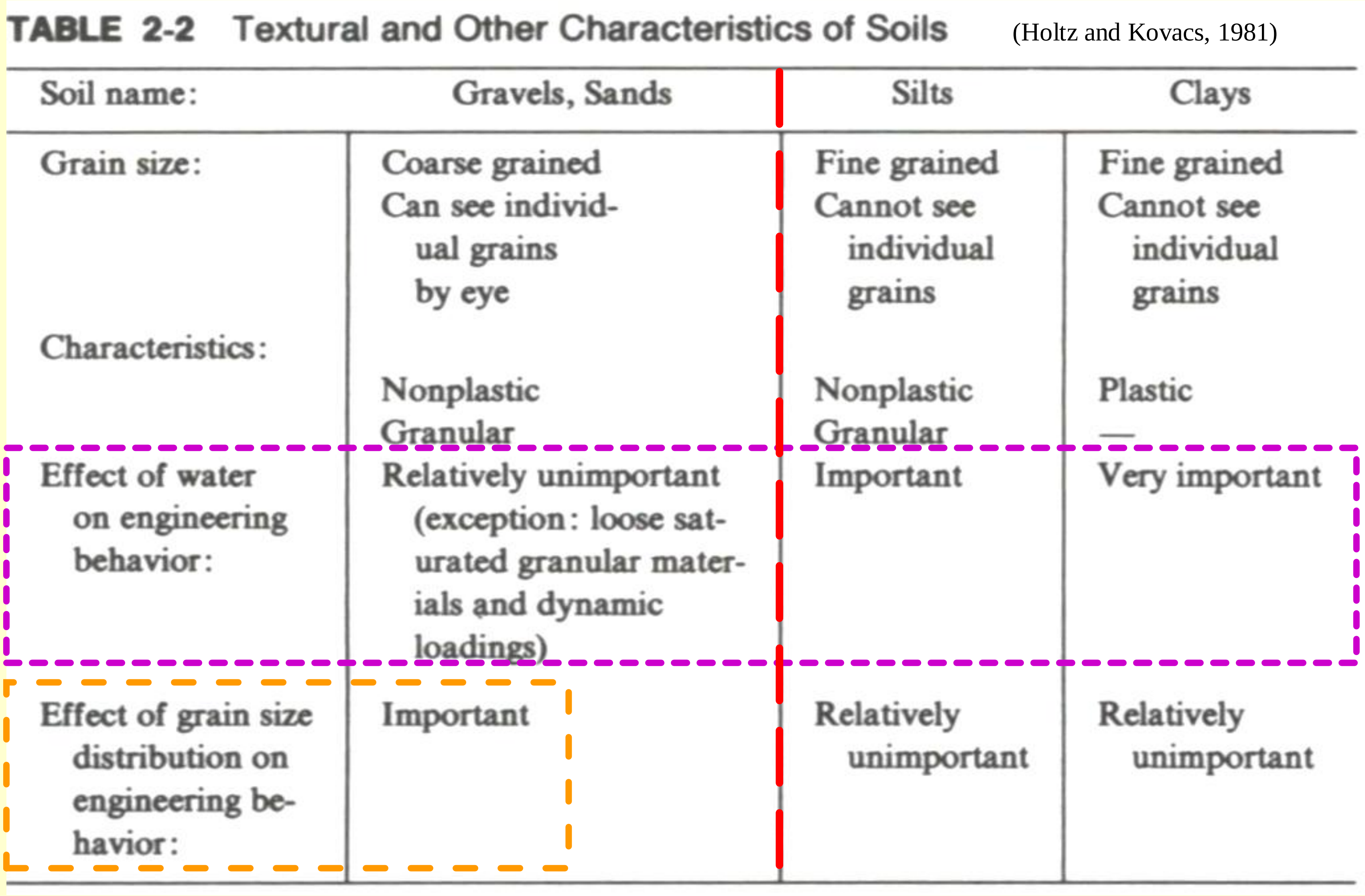
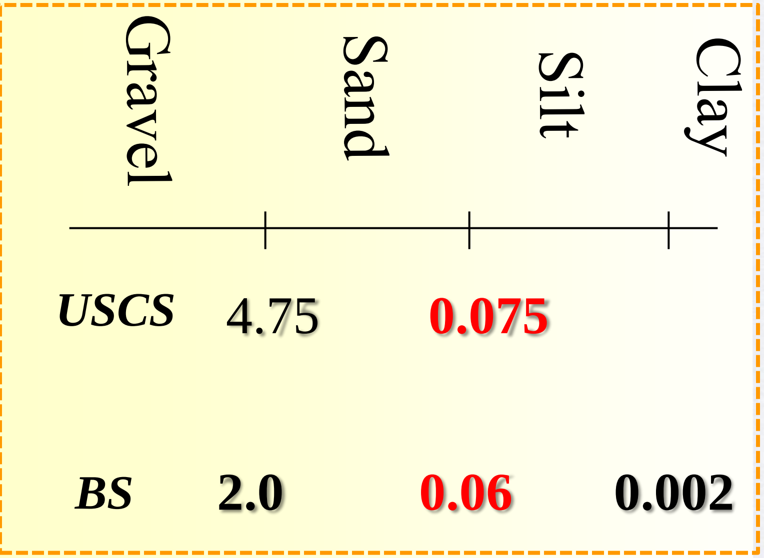


TABLE 2-2 Textural and Other Characteristics of Soils (Holtz and Kovacs, 1981)

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:	Nonplastic Granular	Nonplastic Granular	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

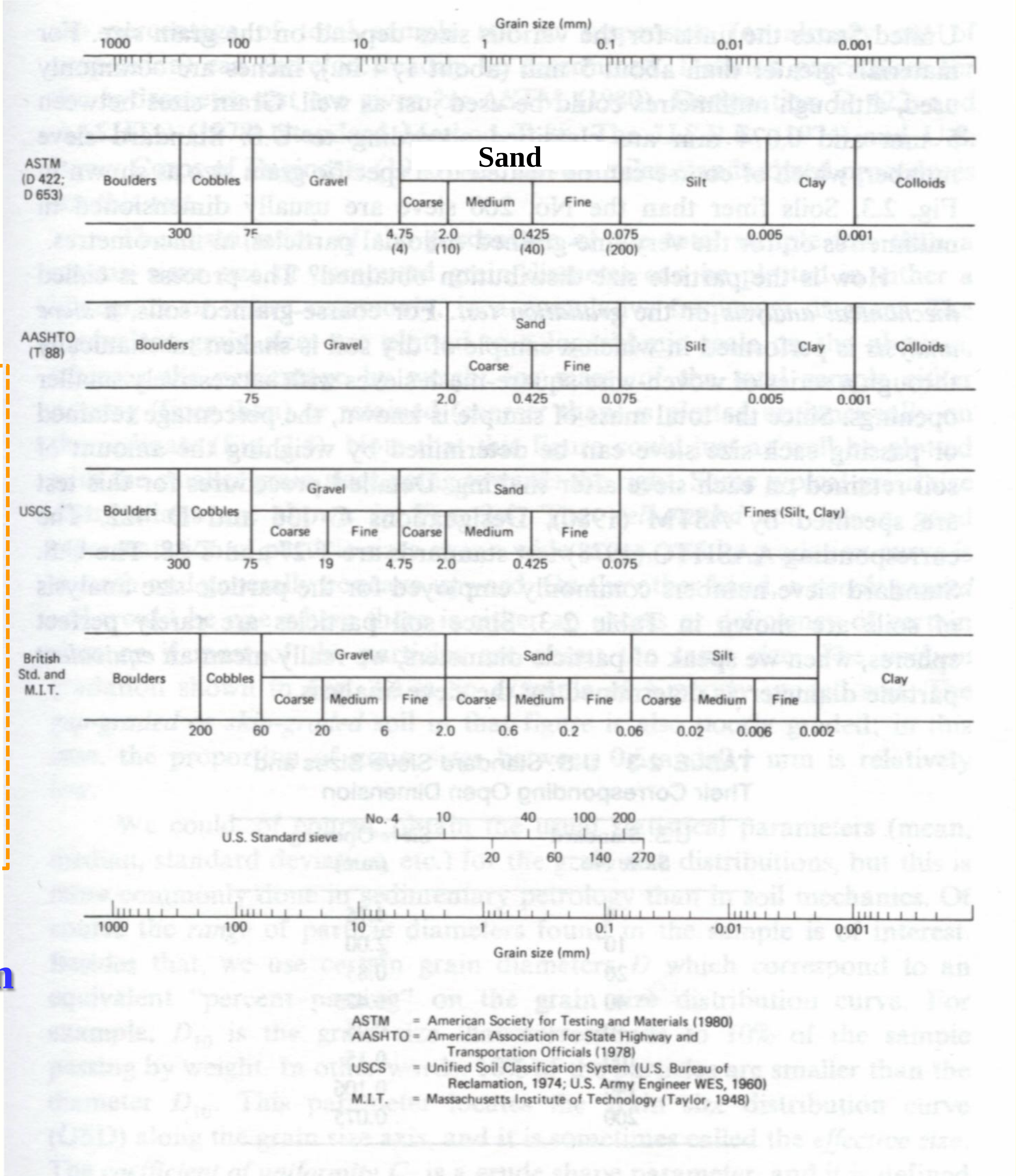
2. Grain Size and Grain Size Distribution

2.1 Grain Size



USCS 4.75 **0.075**

BS **2.0** **0.06** **0.002**



ASTM = American Society for Testing and Materials (1980)
AASHTO = American Association for State Highway and Transportation Officials (1978)
USCS = Unified Soil Classification System (U.S. Bureau of Reclamation, 1974; U.S. Army Engineer WES, 1960)
M.I.T. = Massachusetts Institute of Technology (Taylor, 1948)

Fig. 2.3 Grain size ranges according to several engineering soil classification systems (modified after Al-Hussaini, 1977).

(Holtz and Kovacs, 1981)

USCS: Unified Soil Classification

BS: British Standard

Unit: mm

Note:

Clay-size particles

For example:

A small quartz particle may have the similar size of clay minerals.

Clay minerals

For example:

Kaolinite, Illite, etc.

2.2 Grain Size Distribution

- **Sieve size**

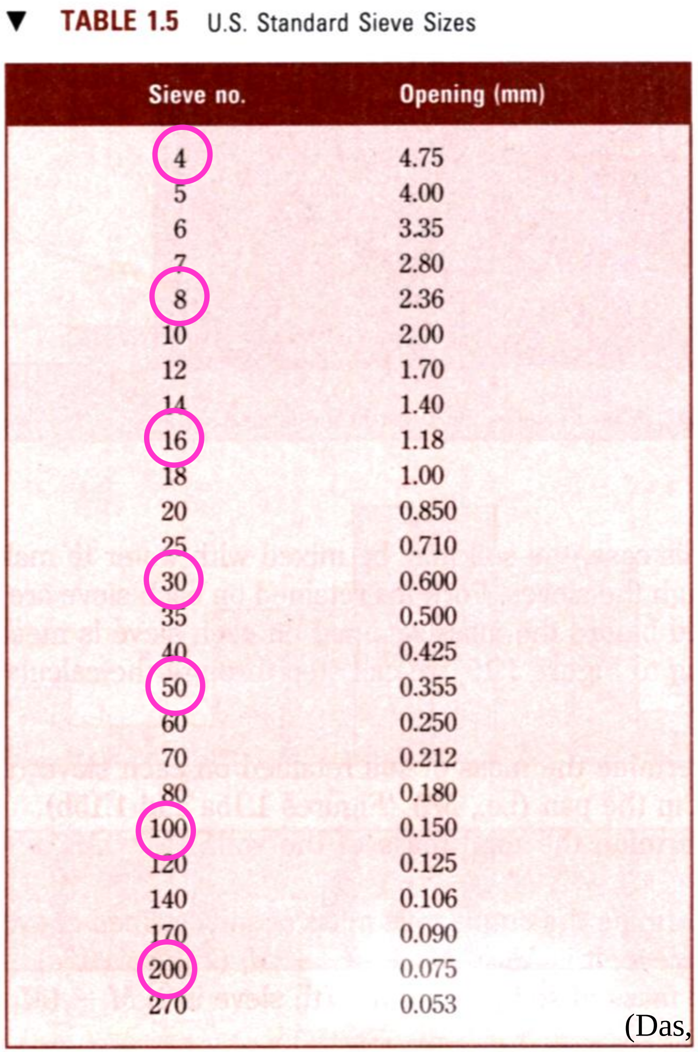


TABLE 1.5 U.S. Standard Sieve Sizes

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

(Das, 1998)

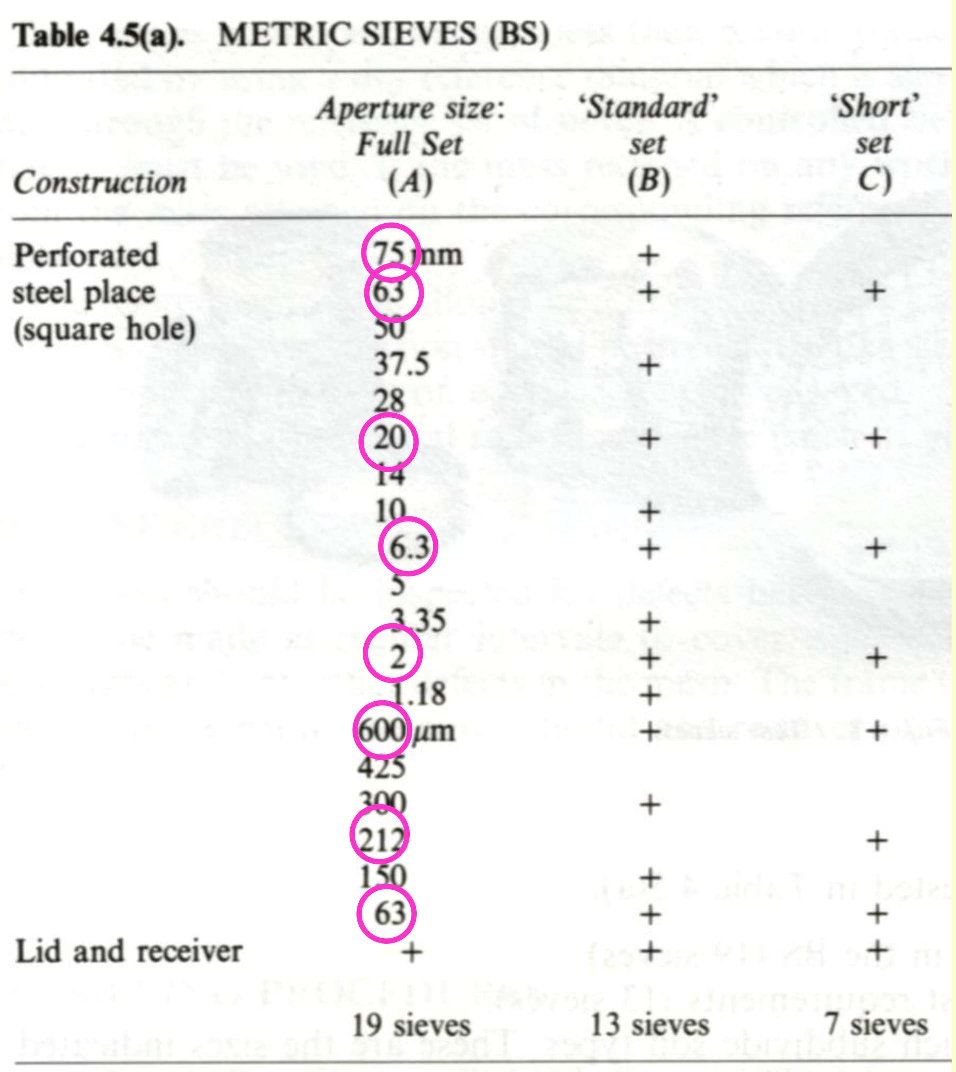


Table 4.5(a). METRIC SIEVES (BS)

Construction	*Aperture size: Full Set (A)*	'Standard' set (B)	'Short' set C)
Perforated steel place (square hole)	75 mm	+	
	63	+	+
	50		
	37.5	+	
	28		
	20	+	+
	14		
	10	+	
	6.3	+	+
	5		
	3.35	+	
	2	+	+
	1.18	+	
	600 μm	+	+
	425		
	300	+	
	212		+
	150	+	
	63	+	+
Lid and receiver	+	+	+
	19 sieves	13 sieves	7 sieves

(Head, 1992)

2.2 Grain Size Distribution (Cont.)

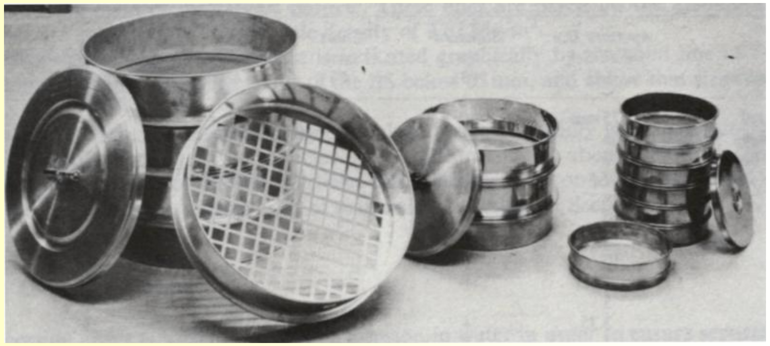
- **Experiment**

Coarse-grained soils: Fine-grained soils:

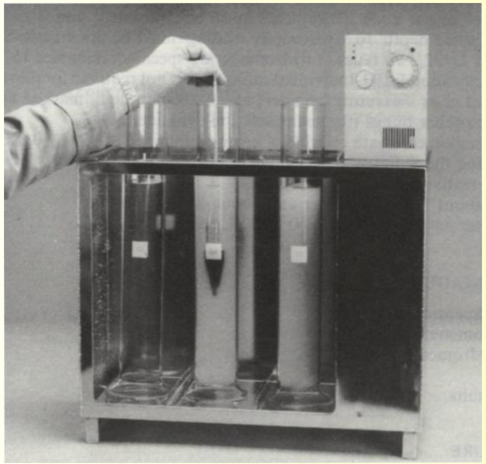
Gravel Sand Silt Clay

0.075 mm (USCS)

0.06 mm (BS)



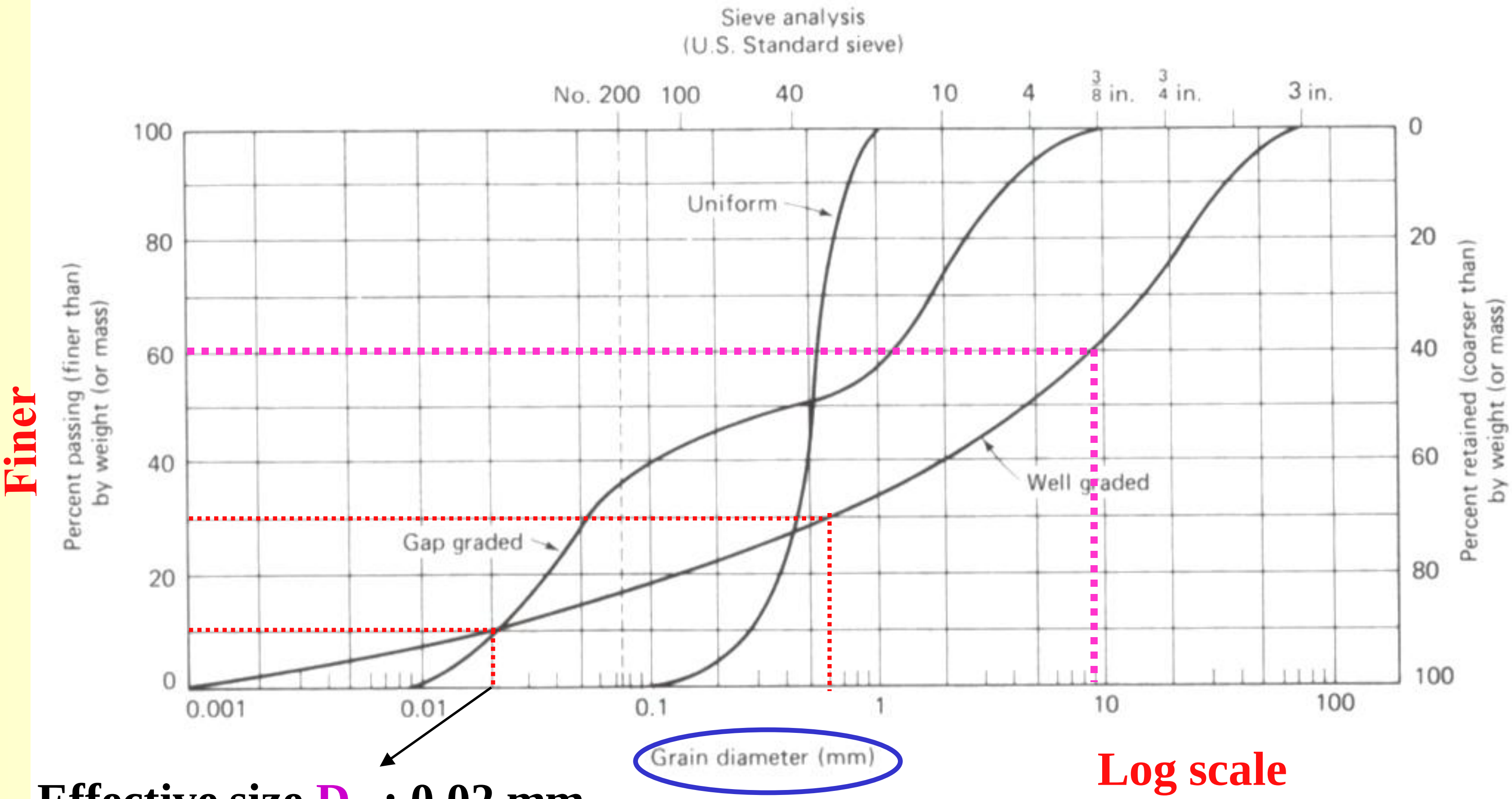
(Head, 1992)



Sieve analysis

Hydrometer analysis

2.2 Grain Size Distribution (Cont.)



Effective size D_{10}: 0.02 mm

Fig. 2.4 Typical grain size distributions.

D_{30}: **D_{60}:**

(Holtz and Kovacs, 1981)

2.2 Grain Size Distribution (Cont.)

- **Describe the shape**

Example: well graded

$$D_{10} = 0.02\,\text{mm (effective size)}$$

$$D_{30} = 0.6\,\text{mm}$$

$$D_{60} = 9\,\text{mm}$$

Coefficient of uniformity

$$C_u = \frac{D_{60}}{D_{10}} = \frac{9}{0.02} = 450$$

Coefficient of curvature

$$C_c = \frac{(D_{30})^2}{(D_{10})(D_{60})} = \frac{(0.6)^2}{(0.02)(9)} = 2$$

- **Criteria**

Well – graded soil

$1 < C_c < 3$ and $C_u \geq 4$

(for gravels)

$1 < C_c < 3$ and $C_u \geq 6$

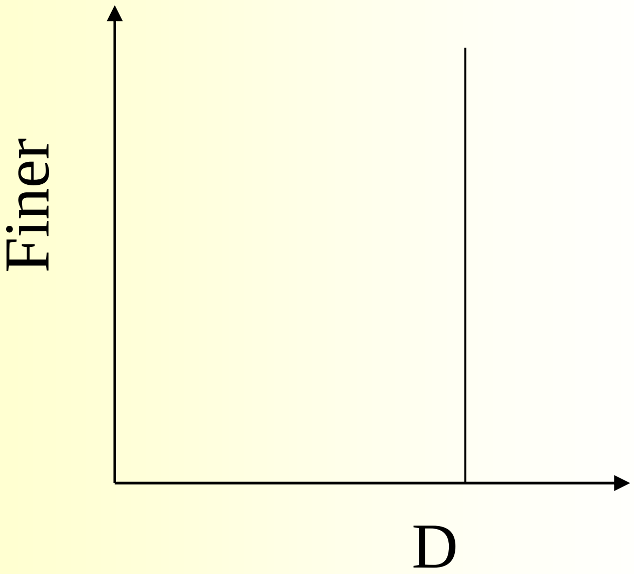
(for sands)

- **Question**

What is the C_u for a soil with only one grain size?

- Question

What is the C_u for a soil with only one grain size?



Grain size distribution

Coefficient of uniformity

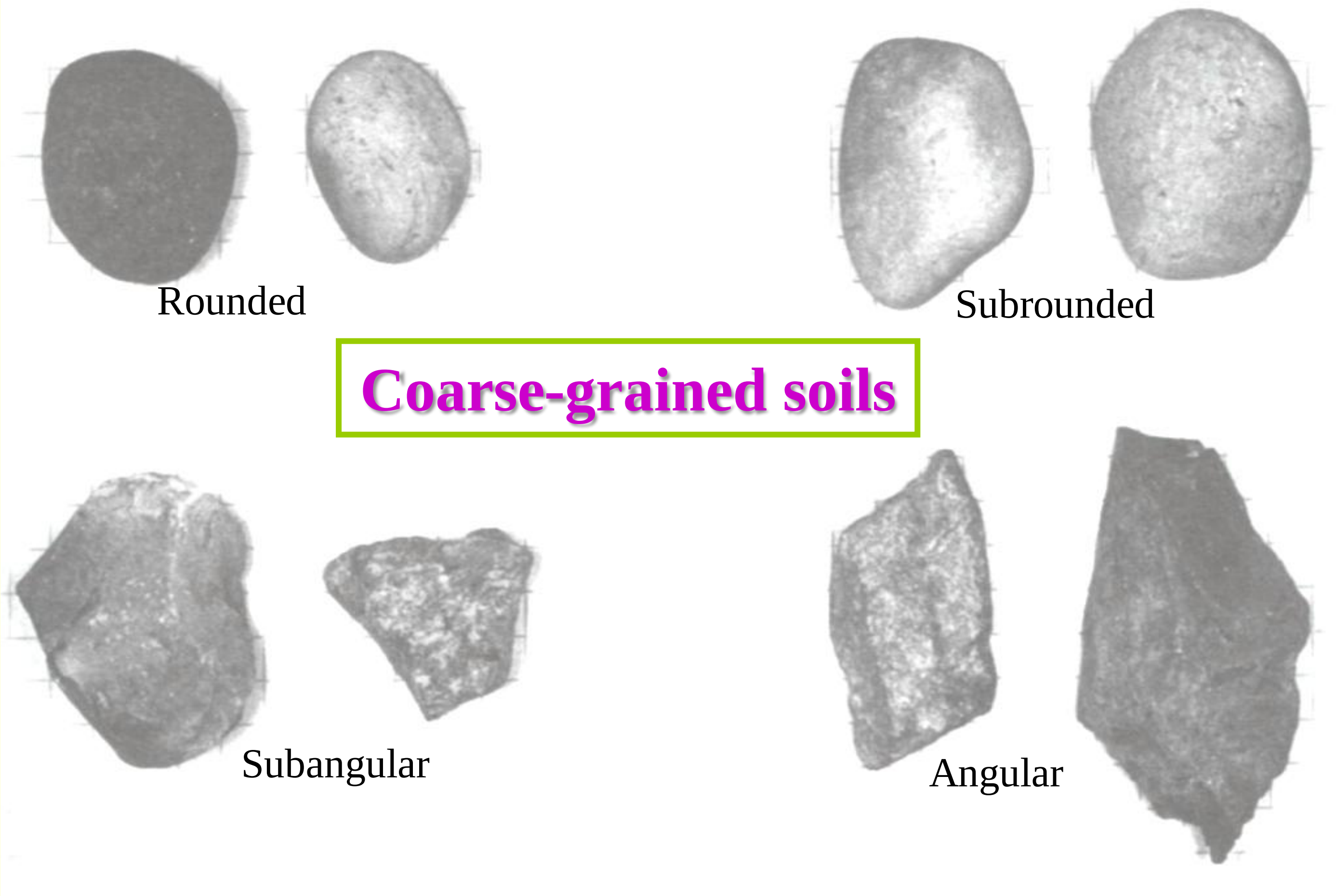
$$C_u = \frac{D_{60}}{D_{10}} = 1$$

2.2 Grain Size Distribution (Cont.)

- **Engineering applications**
  - It will help us "feel" the soil texture (what the soil is) and it will also be used for the ***soil classification* (next topic).**
  - It can be used to define the grading specification of ***a drainage filter (clogging).***
  - It can be a criterion for selecting ***fill materials*** of embankments and earth dams, road sub-base materials, and concrete aggregates.
  - It can be used to estimate the results of **grouting and chemical injection, and dynamic compaction.**
  - **Effective Size, D_{10}**, can be correlated with the **hydraulic conductivity** (describing the permeability of soils). (Hazen's Equation).(Note: controlled by small particles)

The grain size distribution is more important to coarse-grained soils.

3. Particle Shape



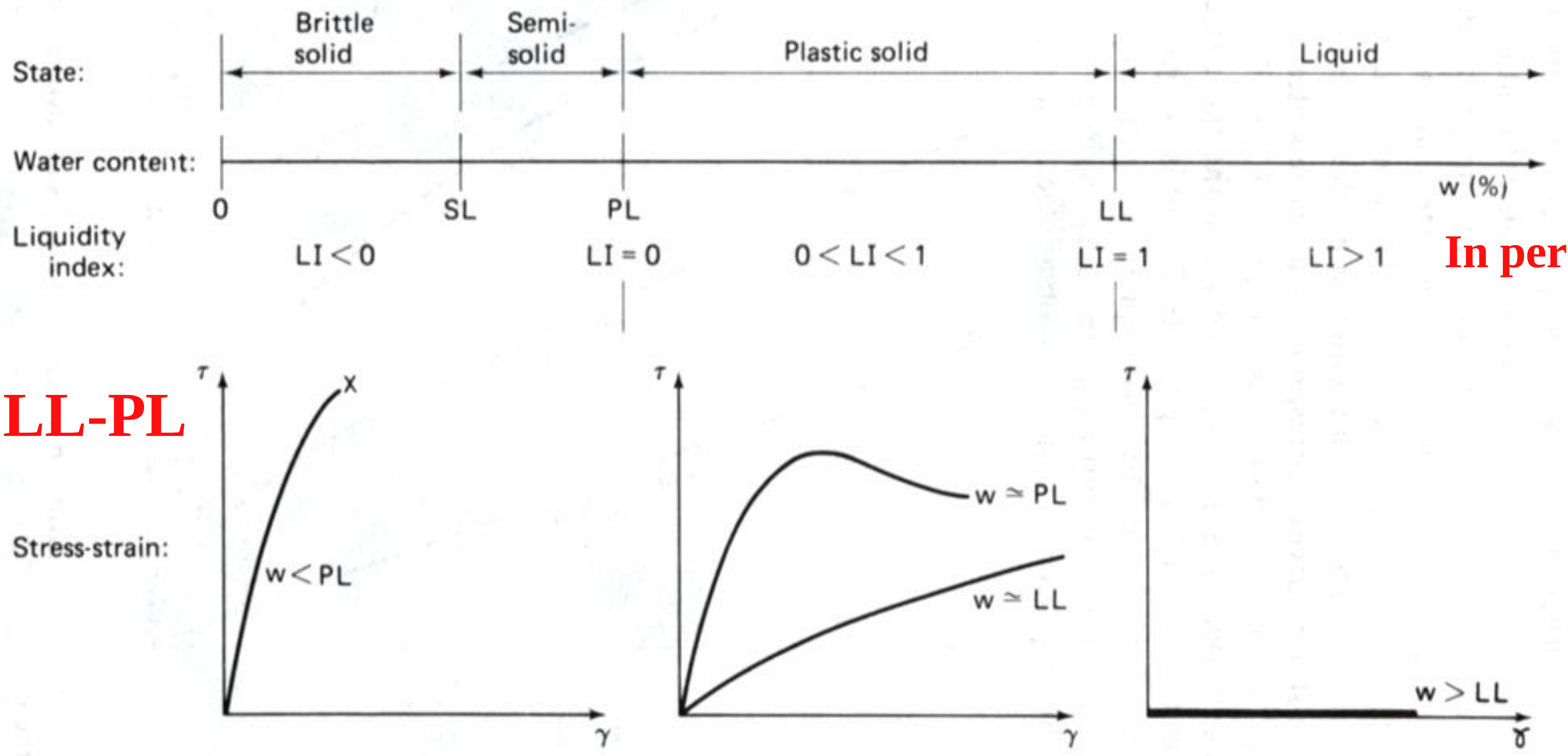
(Holtz and Kovacs, 1981)

- Important for granular soils
- Angular soil particle → higher friction
- Round soil particle → lower friction
- *Note that clay particles are sheet-like.*

4. Atterberg Limits
&
Consistency Indices

4.1 Atterberg Limits

- The presence of water in **fine-grained soils** can significantly affect associated engineering behavior, so we need **a reference index** to clarify the effects. (*The reason will be discussed later in the topic of clay minerals*)



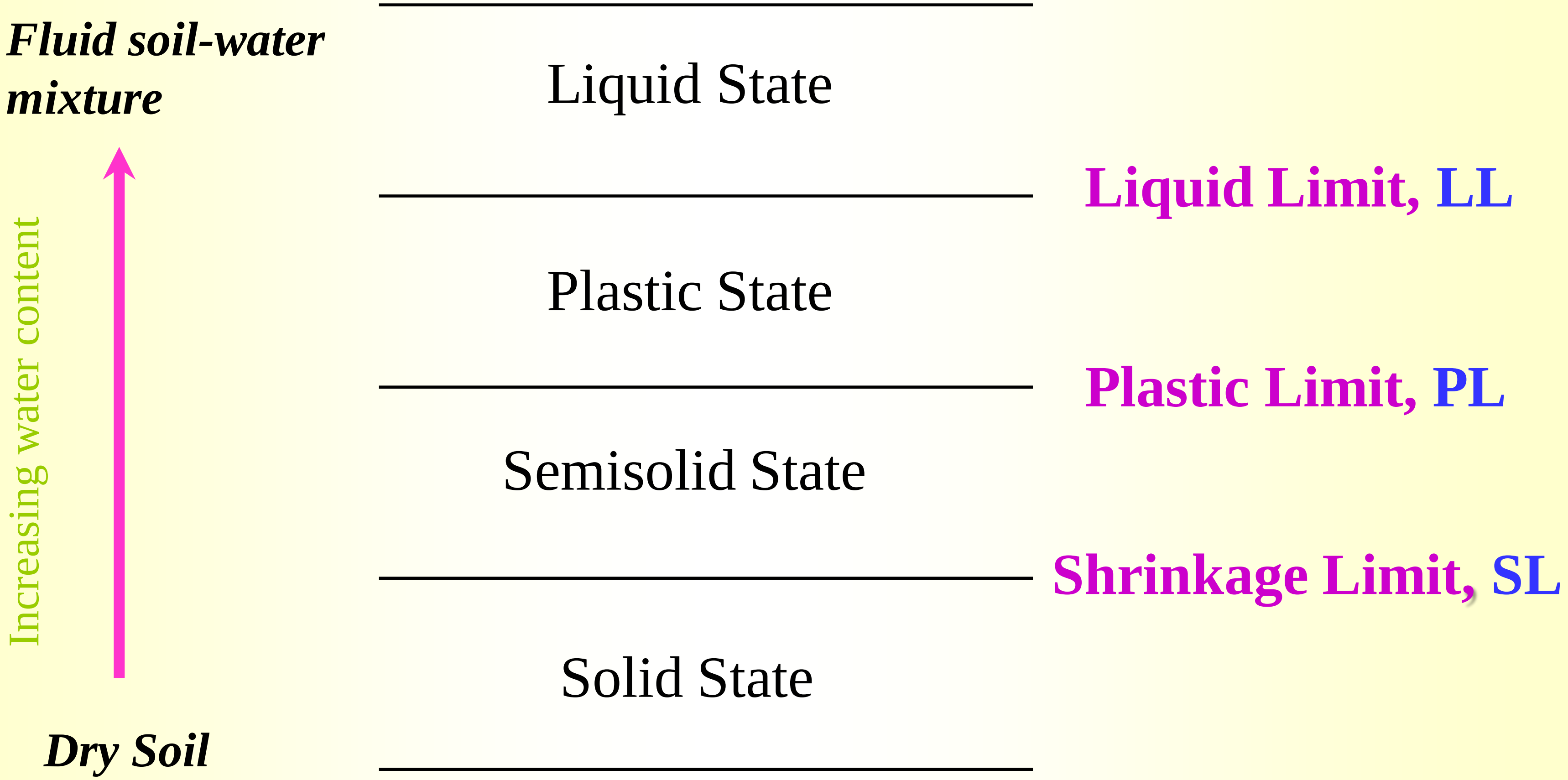
In percentage

PI=LL-PL

Fig. 2.6 Water content continuum showing the various states of a soil as well as the generalized stress-strain response.

(Holtz and Kovacs, 1981)

4.1 Atterberg Limits (Cont.)



Fluid soil-water mixture

Liquid State

Liquid Limit, LL

Plastic State

Plastic Limit, PL

Semisolid State

Shrinkage Limit, SL

Solid State

Dry Soil

Increasing water content

4.2 Liquid Limit-LL

Casagrande Method

(ASTM D4318-95a)

- Professor Casagrande standardized the test and developed the liquid limit device.
- Multipoint test
- One-point test

Cone Penetrometer Method

(BS 1377: Part 2: 1990:4.3)

- This method is developed by the Transport and Road Research Laboratory, UK.
- Multipoint test
- One-point test

4.2 Liquid Limit-LL (Cont.)

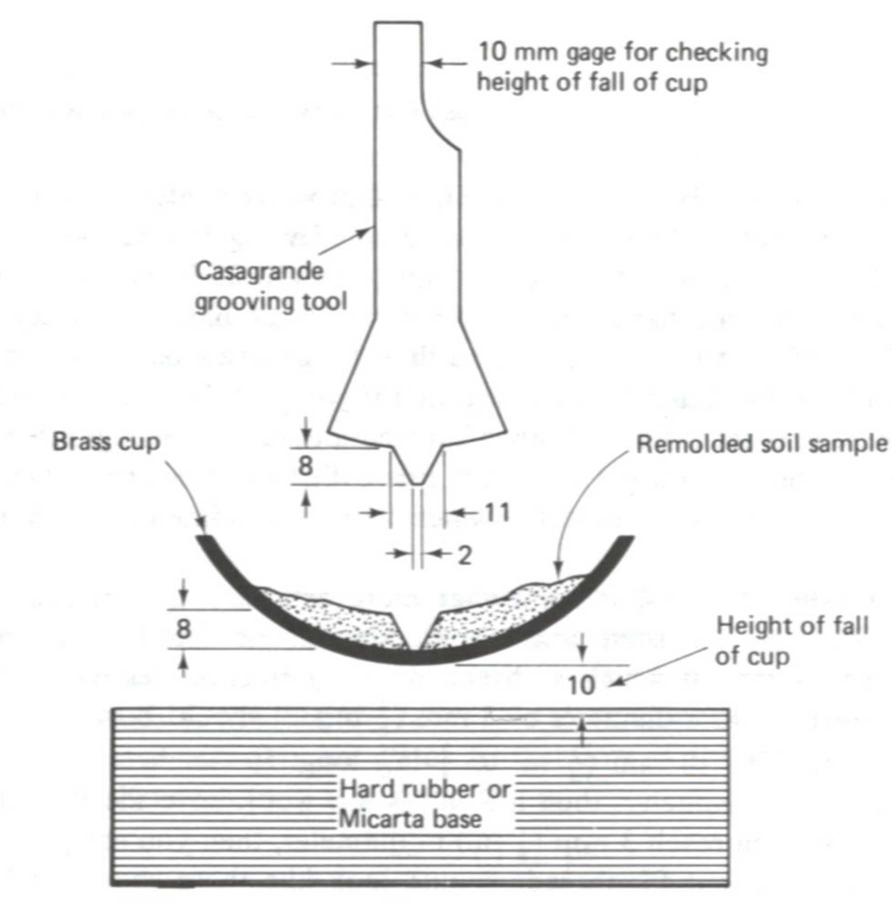
Particle sizes and water

- **Passing No.40 Sieve (0.425 mm).**
- **Using deionized water.**

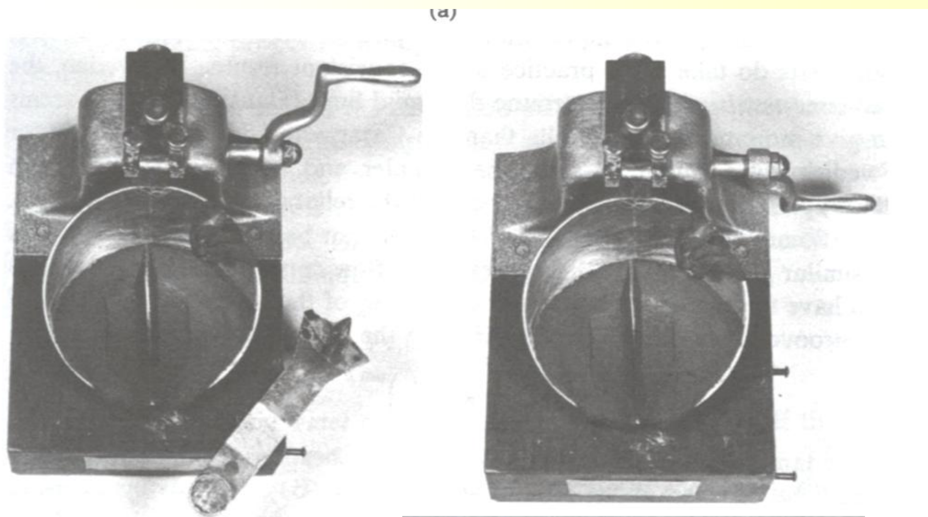
The type and amount of cations can significantly affect the measured results.

4.2.1 Casagrande Method

- **Device**

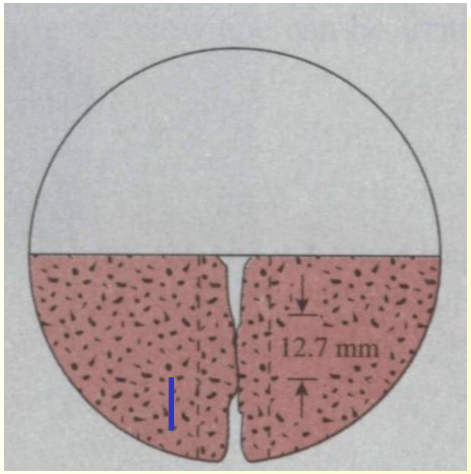


(Holtz and Kovacs, 1981)



N=25 blows

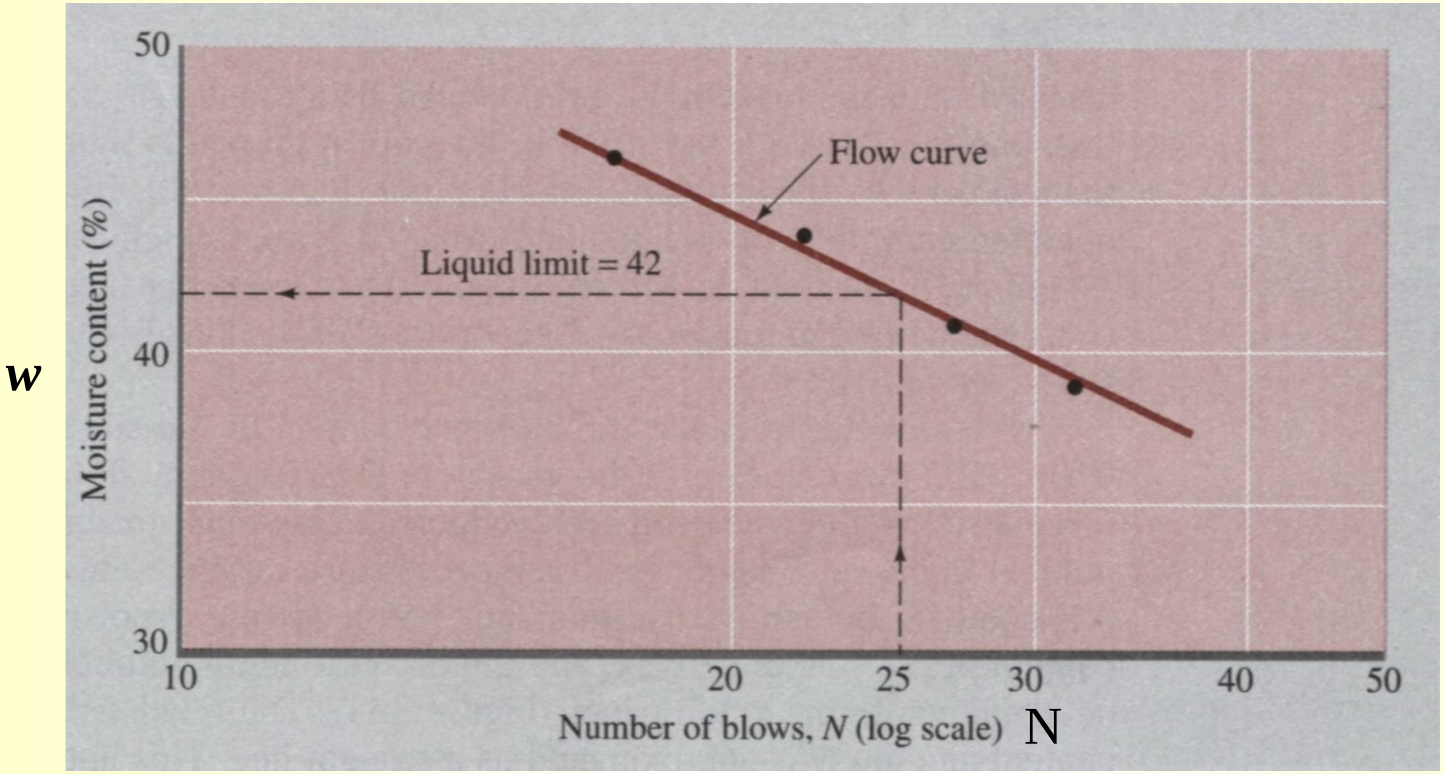
Closing distance = 12.7mm (0.5 in)



The water content, in percentage, required to close a **distance of 0.5 in (12.7mm) along the bottom** of the groove after 25 blows is defined as the liquid limit

4.2.1 Casagrande Method (Cont.)

- **Multipoint Method**



Das, 1998

$$Flow\ index, I_F = \frac{w_1 - w_2}{\log(N_2 / N_1)}\ (choose\ a\ \ positive\ value)$$

$$w = -I_F \log N + cont.$$

4.2.1 Casagrande Method (Cont.)

•One-point Method

- Assume a constant slope of the flow curve.
- The slope is a statistical result of **767 liquid limit** tests.

$$LL = w_n \left(\frac{N}{25} \right)^{\tan\beta}$$

$$N = number\ of\ blows$$

$$w_n = corresponding\ \ moisture\ content$$

$$\tan\beta = 0.121$$

Limitations:

- The β is an empirical coefficient, so it is not always 0.121.
- Good results can be obtained only for the blow number around **20 to 30.**

4.2.2 Cone Penetrometer Method

- **Device**

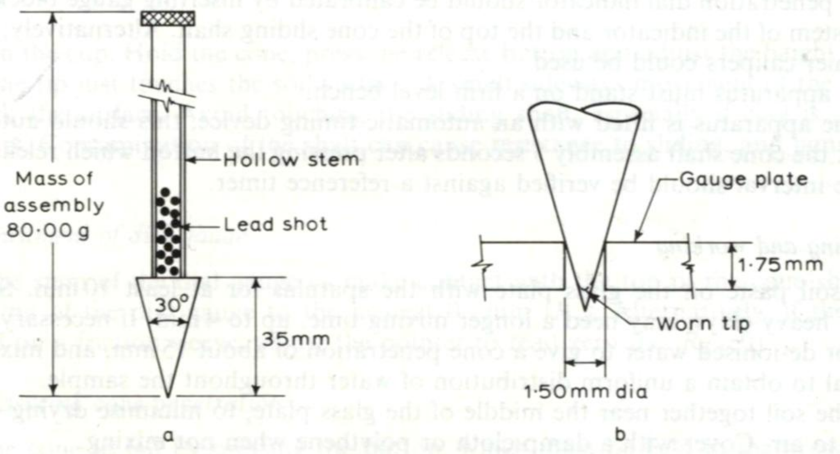
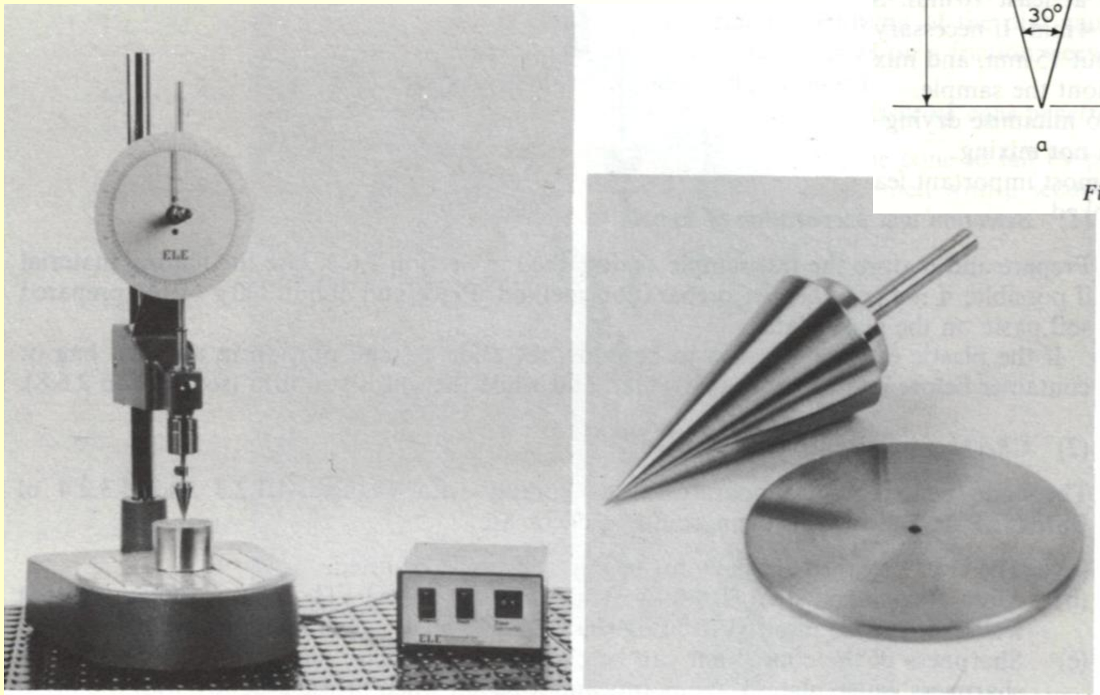


Fig. 2.12 Details of cone for penetrometer



(a) (b)

Fig. 2.11 *Apparatus for cone penetrometer liquid test: (a) Cone penetrometer with automatic timing device, (b) cone and gauge plate*

This method is developed by the Transport and Road Research Laboratory. (Head, 1992)

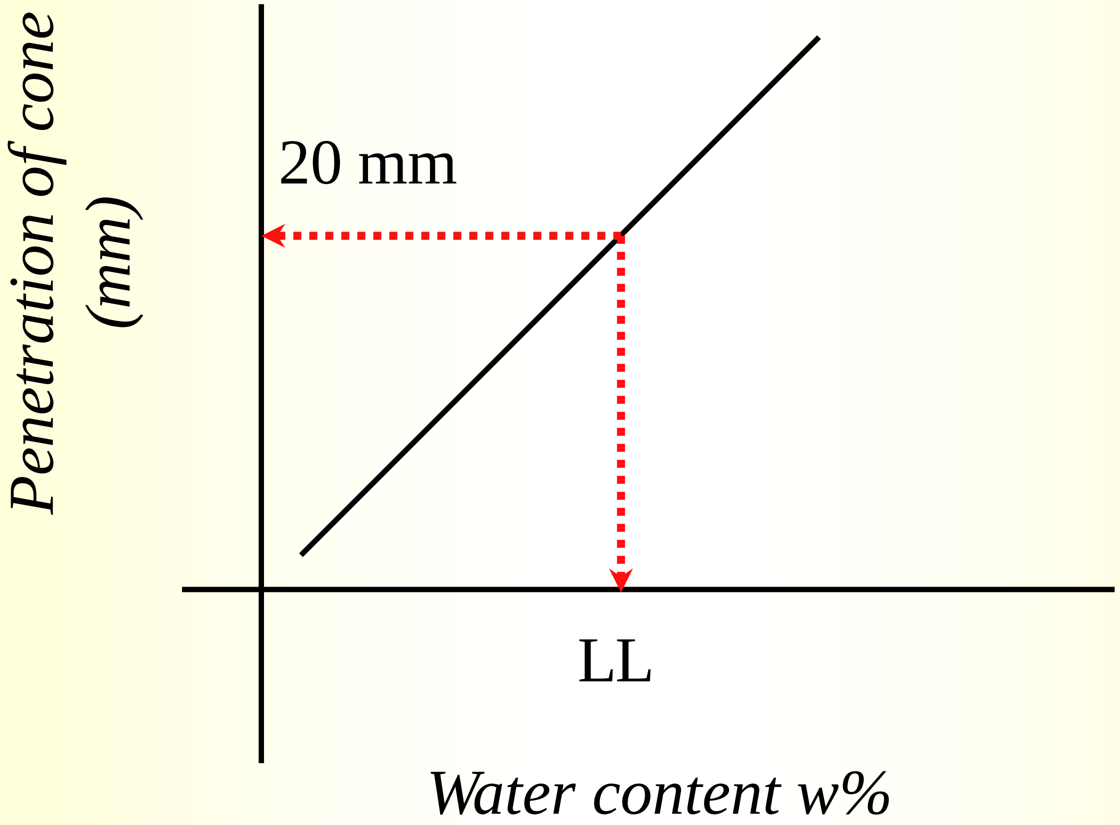
Allowable time to penetrate the cone = 5 ± 1 sec

4.2.2 Cone Penetrometer Method (Cont.)

- **Multipoint Method**

Between 15 mm and 25 mm

and as close as possible to 20 mm



4.2.2 Cone Penetrometer Method (Cont.)

- **One-point Method (an empirical relation)**

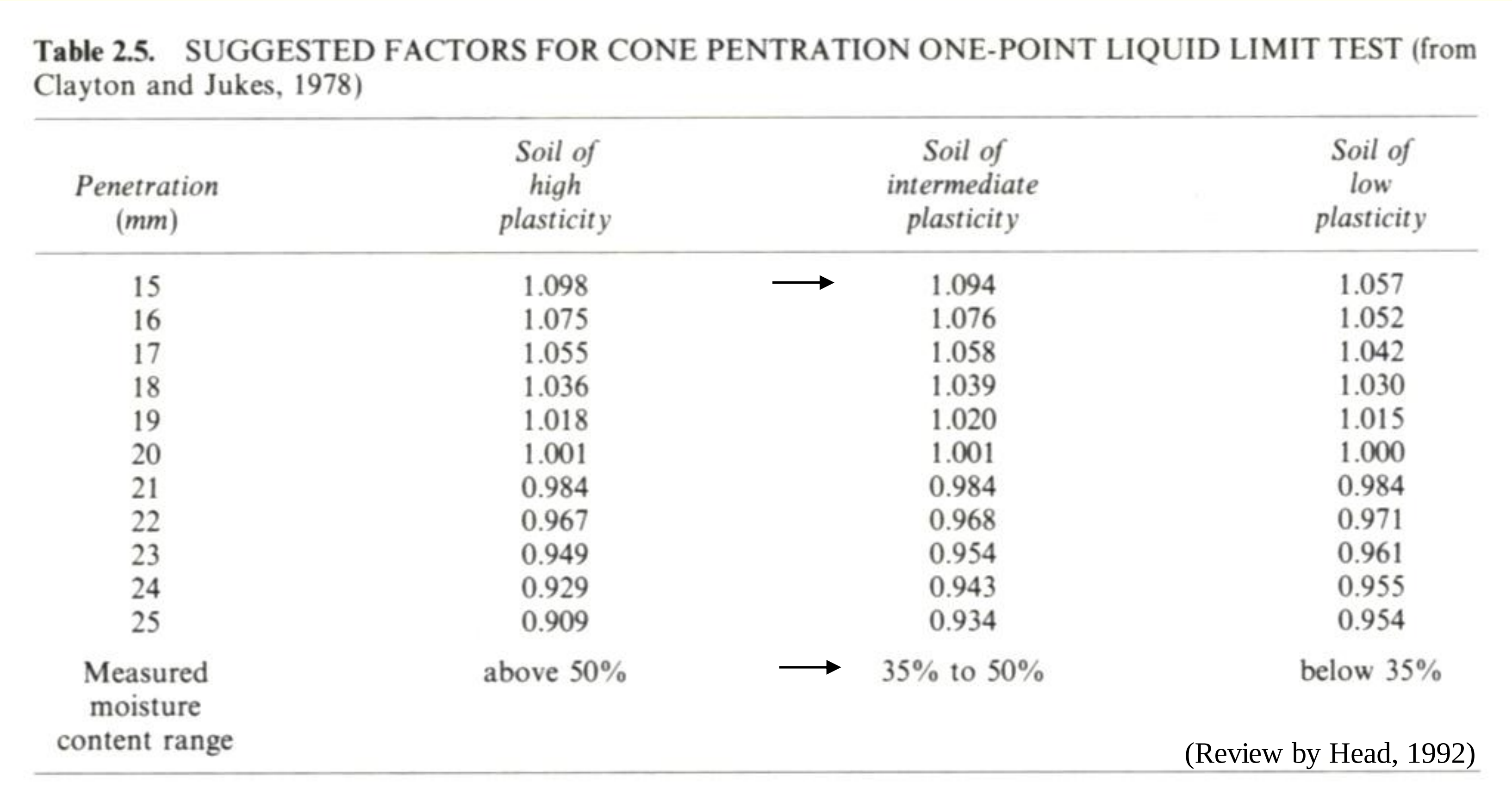


Table 2.5. SUGGESTED FACTORS FOR CONE PENTRATION ONE-POINT LIQUID LIMIT TEST (from Clayton and Jukes, 1978)

Penetration (*mm*)	*Soil of high plasticity*	*Soil of intermediate plasticity*	*Soil of low plasticity*
15	1.098	→ 1.094	1.057
16	1.075	1.076	1.052
17	1.055	1.058	1.042
18	1.036	1.039	1.030
19	1.018	1.020	1.015
20	1.001	1.001	1.000
21	0.984	0.984	0.984
22	0.967	0.968	0.971
23	0.949	0.954	0.961
24	0.929	0.943	0.955
25	0.909	0.934	0.954
Measured moisture content range	above 50%	→ 35% to 50%	below 35%

(Review by Head, 1992)

Example: $\text{Penetration depth} = 15\,\text{mm},\ w = 40\%,$

$\text{Factor} = 1.094,\ \text{LL} = 40 \cdot 1.094 \approx 44$

LL=Water content* Factor

4.2.3 Comparison

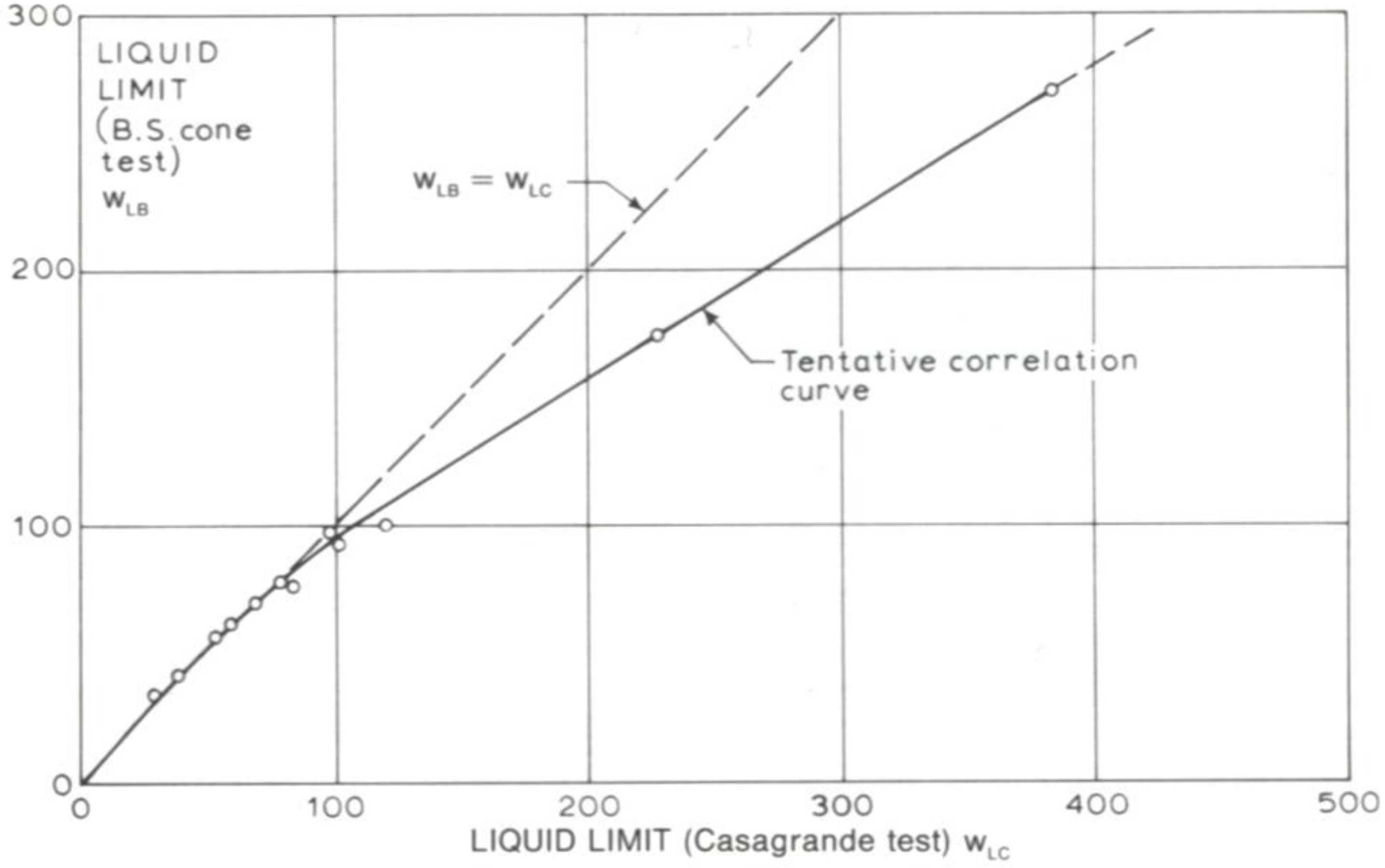


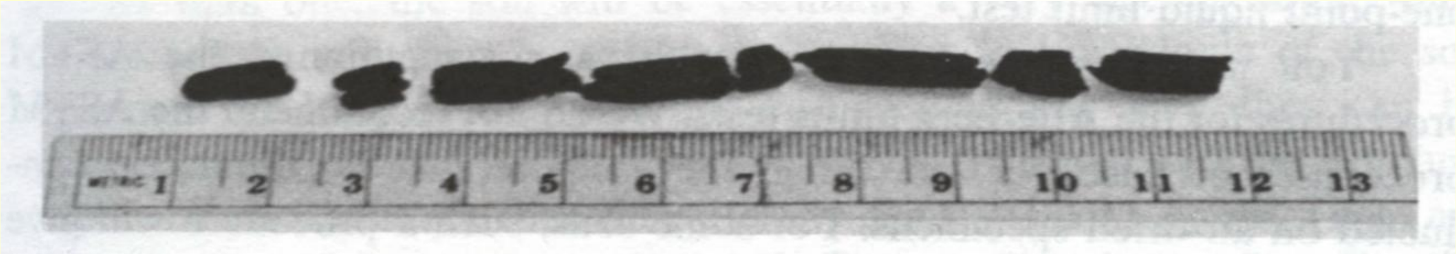
Fig. 2.9 Correlation of liquid limit results from two test methods

Littleton and Farmilo, 1977 (from Head, 1992)

A good correlation between the two methods can be observed as the LL is less than 100.

Question:
Which method will render more consistent results?

4.3 Plastic Limit-PL

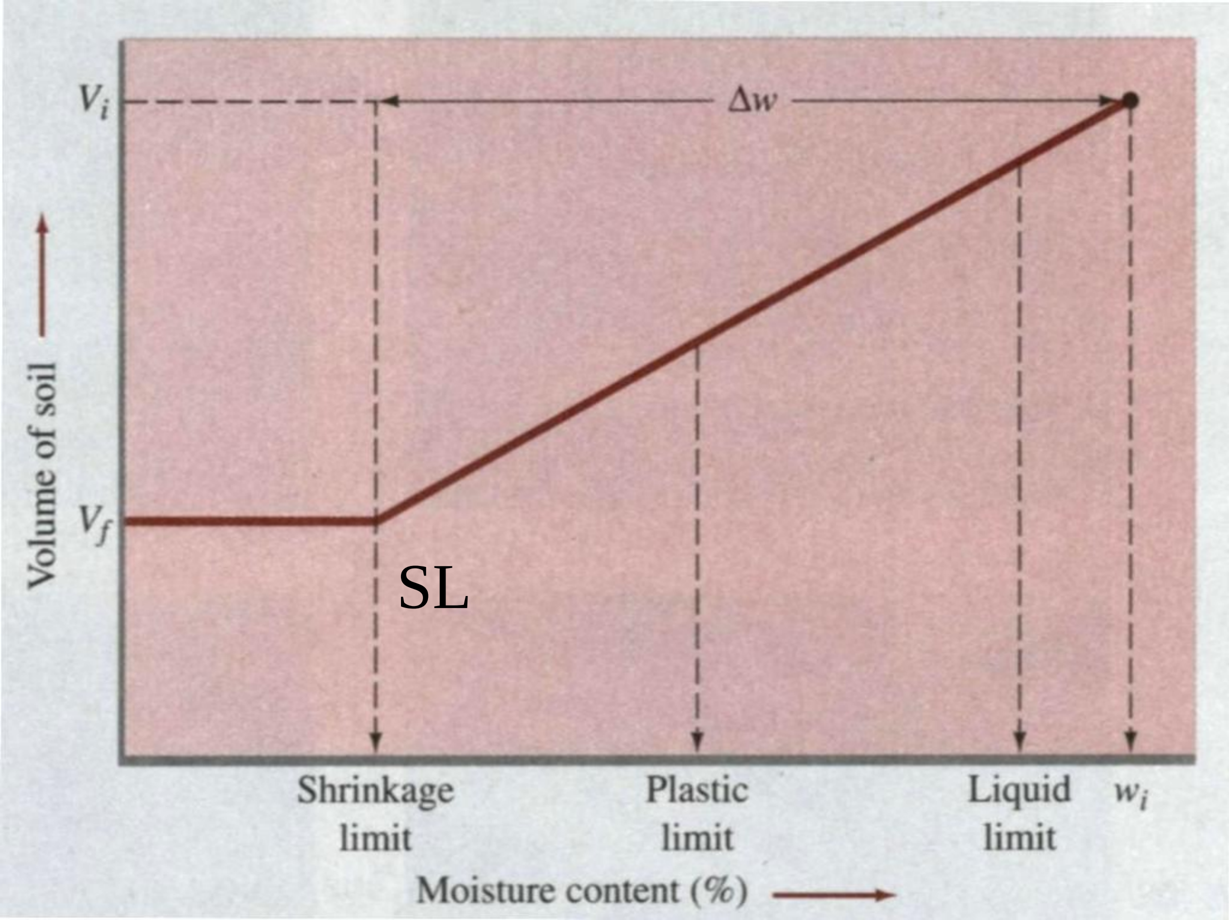


(Holtz and Kovacs, 1981)

The plastic limit PL is defined as the water content at which a soil thread with ***3.2 mm diameter just*** crumbles.

ASTM D4318-95a, BS1377: Part 2:1990:5.3

4.4 Shrinkage Limit-SL

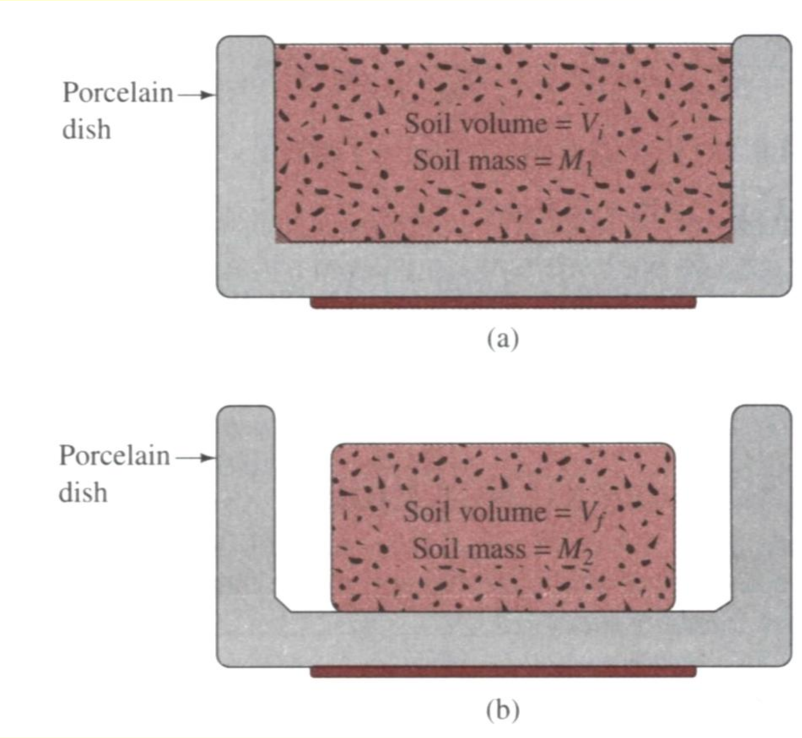


(Das, 1998)

Definition of shrinkage limit:

The water content at which the soil volume ceases to change is defined as the shrinkage limit.

4.4 Shrinkage Limit-SL (Cont.)



Soil volume: V_i

Soil mass: M_1

Soil volume: V_f

Soil mass: M_2

(Das, 1998)

$$SL = w_i(\%) - \Delta w(\%)$$

$$= \left(\frac{M_1 - M_2}{M_2}\right)(100) - \left(\frac{V_i - V_f}{M_2}\right)(\rho_w)(100)$$

4.4 Shrinkage Limit-SL (Cont.)

- “Although the shrinkage limit was a popular classification test during the 1920s, it is subject to **considerable uncertainty and thus is no *longer commonly conducted***.”

- “One of the **biggest problems** with the shrinkage limit test is that the amount of shrinkage depends ***not only on the grain size but also on the initial fabric of the soil***. The standard procedure is to start with the water content near the liquid limit. However, especially with sandy and silty clays, this often results in a shrinkage limit greater than the plastic limit, which is meaningless. Casagrande suggests that the initial water content be slightly greater than the PL, if possible, but admittedly it is difficult to avoid entrapping air bubbles.” (from Holtz and Kovacs, 1981)

4.5 Typical Values of Atterberg Limits

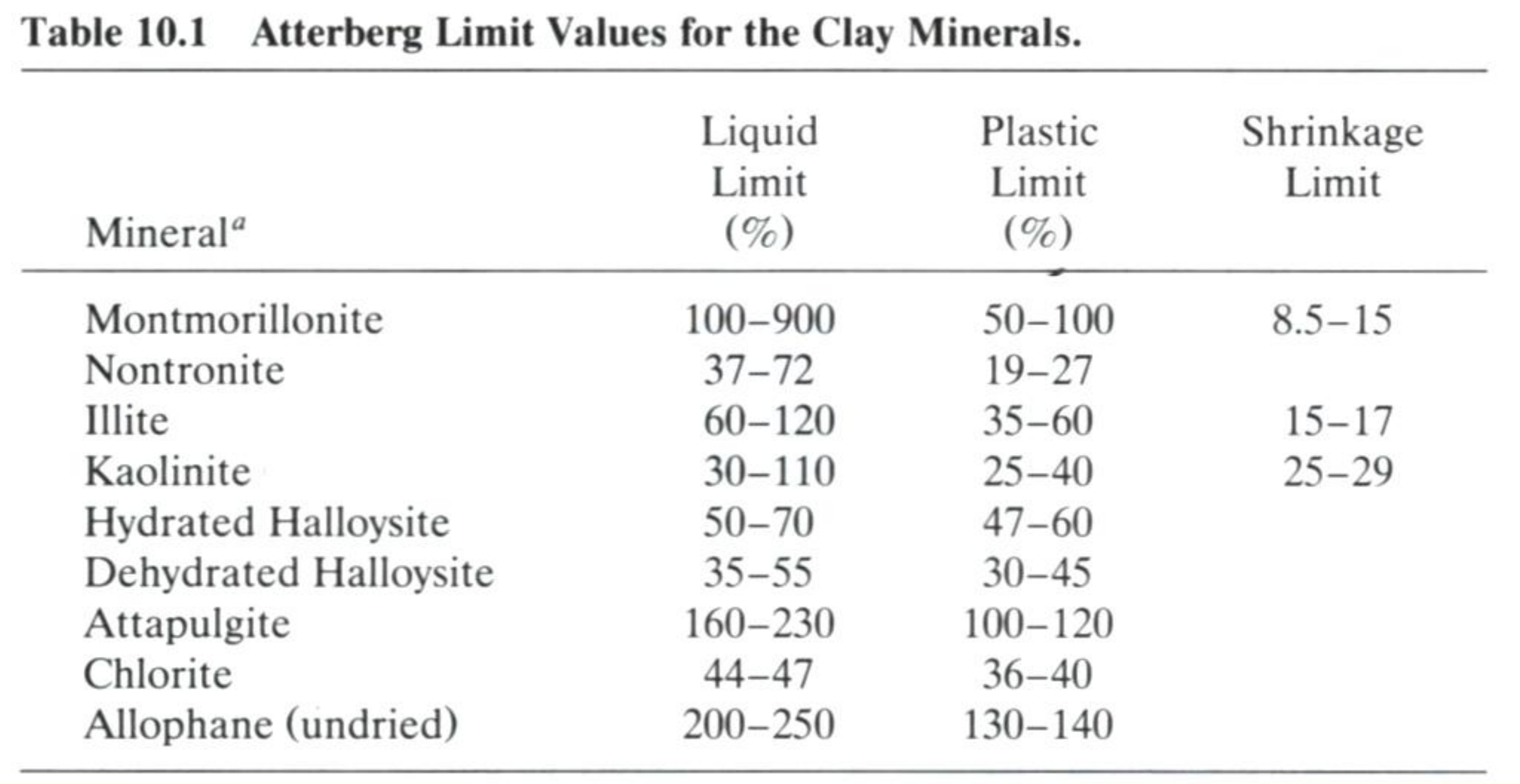


Table 10.1 Atterberg Limit Values for the Clay Minerals.

Mineral[a]	Liquid Limit (%)	Plastic Limit (%)	Shrinkage Limit
Montmorillonite	100–900	50–100	8.5–15
Nontronite	37–72	19–27	
Illite	60–120	35–60	15–17
Kaolinite	30–110	25–40	25–29
Hydrated Halloysite	50–70	47–60	
Dehydrated Halloysite	35–55	30–45	
Attapulgite	160–230	100–120	
Chlorite	44–47	36–40	
Allophane (undried)	200–250	130–140	

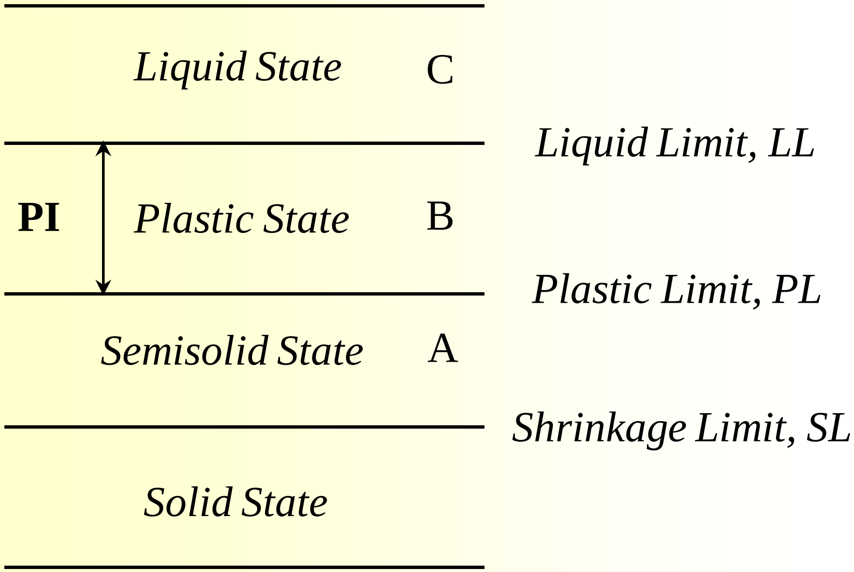
(Mitchell, 1993)

4.6 Indices

- **Plasticity index PI**

For describing the range of water content over which a soil was plastic

PI = LL – PL



Liquid State C

Liquid Limit, LL

PI *Plastic State* B

Plastic Limit, PL

Semisolid State A

Shrinkage Limit, SL

Solid State

- **Liquidity index LI**

For scaling the natural water content of a soil sample to the Limits.

$$LI = \frac{w - PL}{PI} = \frac{w - PL}{LL - PL}$$

w is the water content

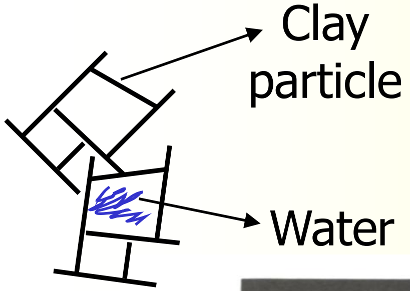
LI <0 (A), brittle fracture if sheared

0<LI<1 (B), plastic solid if sheared

LI >1 (C), viscous liquid if sheared

4.6 Indices (Cont.)

- **Sensitivity S_t** (for clays)



$w > \mathrm{LL}$

$$S_t = \frac{\text{Strength (undisturbed)}}{\text{Strength (disturbed)}}$$

Unconfined shear strength

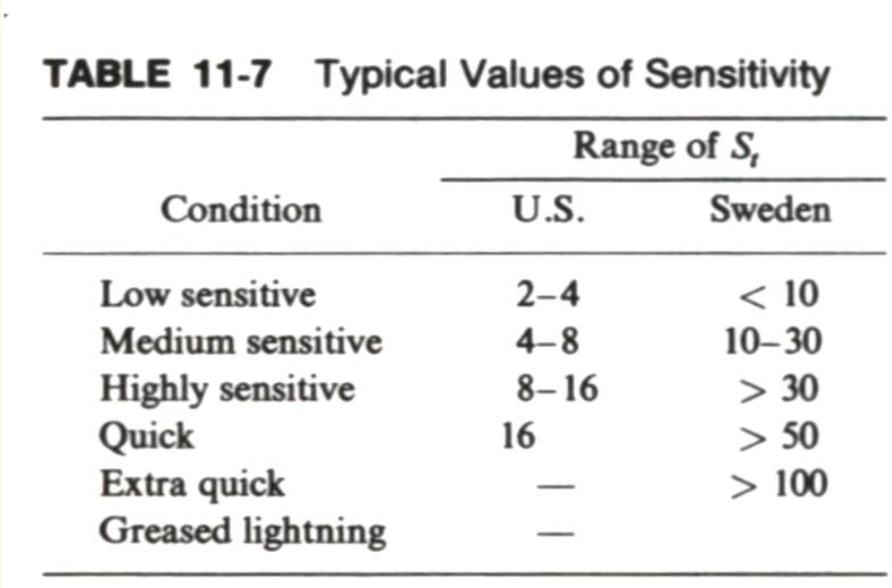


TABLE 11-7 Typical Values of Sensitivity

Condition	Range of S_t U.S.	Range of S_t Sweden
Low sensitive	2–4	< 10
Medium sensitive	4–8	10–30
Highly sensitive	8–16	> 30
Quick	16	> 50
Extra quick	—	> 100
Greased lightning	—	

(Holtz and Kavocs, 1981)

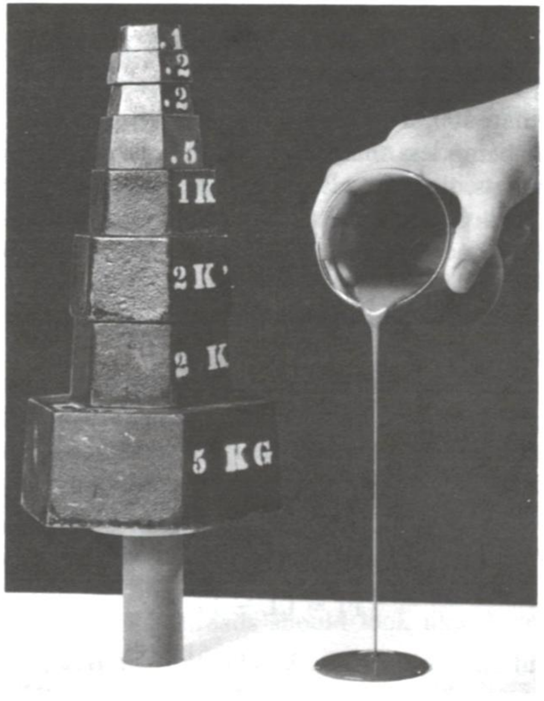


Fig. 2.9 (a) Undisturbed and (b) thoroughly remolded sample of Leda clay from Ottawa, Ontario. (Photograph courtesy of the Division of Building Research, National Research Council of Canada. Hand by D. C. MacMillan.)

4.6 Indices (Cont.)

- **Activity A**

(Skempton, 1953)

$$A = \frac{PI}{\%\,\text{clay fraction (weight)}}$$

$$\text{clay fraction} : < 0.002\ \text{mm}$$

Normal clays: 0.75<A<1.25

Inactive clays: A<0.75

Active clays: A> 1.25

High activity:

- large volume change when wetted
- Large shrinkage when dried
- Very reactive (chemically)

- **Purpose**

Both **the** ***type*** **and** ***amount*** of clay in soils will affect the Atterberg limits. This index is aimed to separate them.

Mitchell, 1993

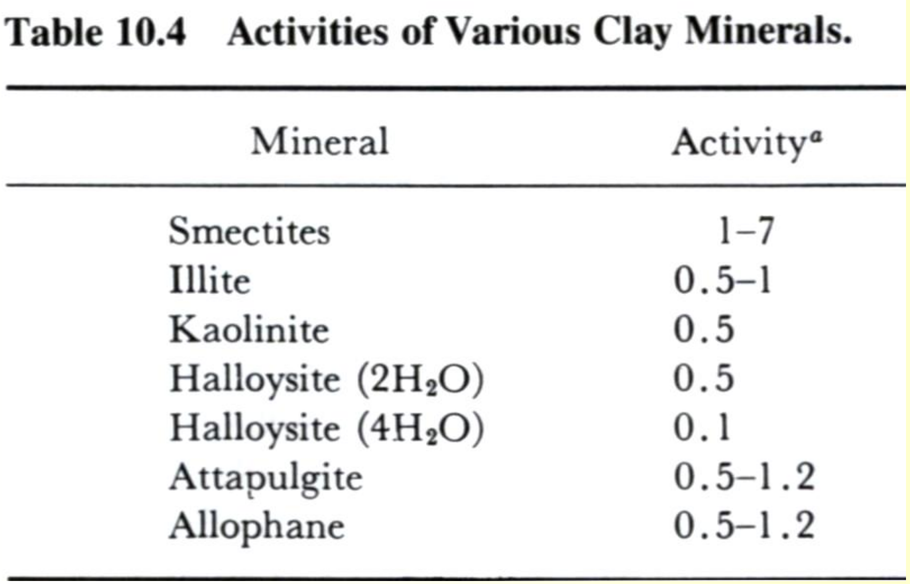


Table 10.4 Activities of Various Clay Minerals.

Mineral	Activity[a]
Smectites	1–7
Illite	0.5–1
Kaolinite	0.5
Halloysite ($2H_2O$)	0.5
Halloysite ($4H_2O$)	0.1
Attapulgite	0.5–1.2
Allophane	0.5–1.2

4.7 Engineering Applications

- **Soil classification**

  (the next topic)

  – The Atterberg limit enable clay soils to be classified.

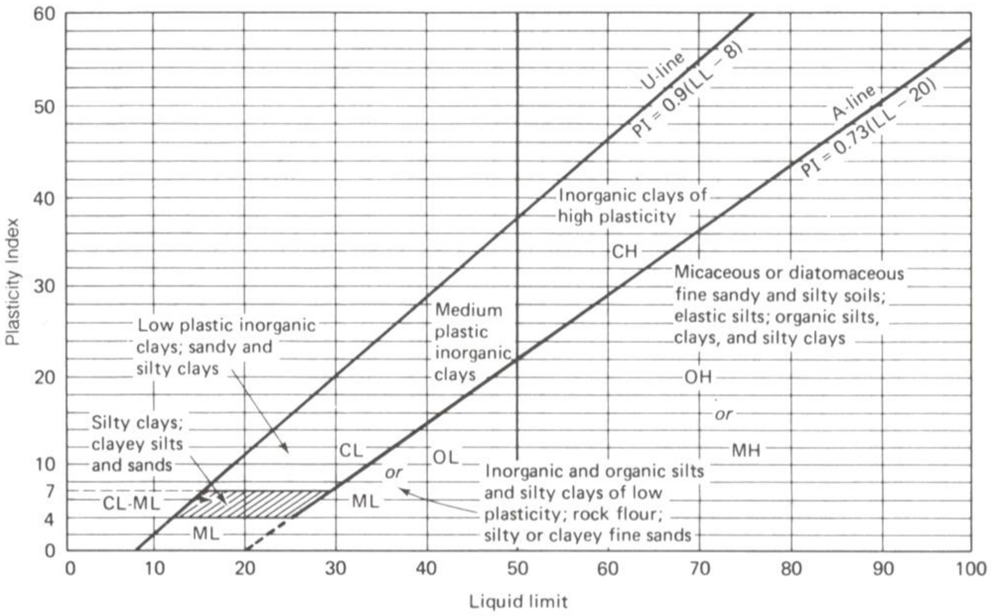


Fig. 3.2 Casagrande's plasticity chart, showing several representative soil types (developed from Casagrande, 1948, and Howard, 1977).

- The Atterberg limits are usually correlated with some engineering properties such as the **permeability, compressibility, shear strength, and others.**
  - In general, clays with high plasticity have lower permeability, and they are difficult to be compacted.
  - The values of SL can be used as a criterion to assess and prevent the excessive cracking of clay liners in the reservoir embankment or canal.

5. Some Thoughts about the Sieve Analysis

- Wet analysis
  - For “**clean**” sands and gravels **dry sieve analysis** can be used.
  - If soils contain **silts and clays**, the **wet sieving** is usually used to preserve the fine content.

6. Some Thoughts about the Hydrometer Analysis

Stokes' law

$$v = \frac{(\gamma_s - \gamma_w)D^2}{18\eta}$$

(Compiled from Lambe, 1991)

Assumption	**Reality**
Sphere particle	Platy particle (clay particle) as D ≤ *0.005mm*
Single particle (No interference between particles)	Many particles in the suspension
Known specific gravity of particles	Average results of all the minerals in the particles, including the adsorbed water films. ***Note:*** the adsorbed water films also can increase the resistance during particle settling.
Terminal velocity	Brownian motion as D ≤ *0.0002 mm*

1. Please derive the equation for calculating the percentage finer than D (hint: please see the note).

$$\text{Percentage finer than } D = \frac{100 G_s D^2}{G_s - 1}\left(\frac{R_d}{m}\right)\%$$

2. Please understand the calibration of hydrometer.

$H_r = 200.4 - 3.90 R_h$ *Please understand how to get this equation.*

3. Please go over examples

7. References

Main References:

Das, B.M. (1998). *Principles of Geotechnical Engineering*, 4th edition, PWS Publishing Company. (Chapter 2)

Holtz, R.D. and Kovacs, W.D. (1981). *An Introduction to Geotechnical Engineering*, Prentice Hall. (Chapter 1 and 2)

Head, K. H. (1992). *Manual of Soil Laboratory Testing, Volume 1: Soil Classification and*.