آزمایشگاه مکانیک خاک

Karl Terzaghi
1883-1963

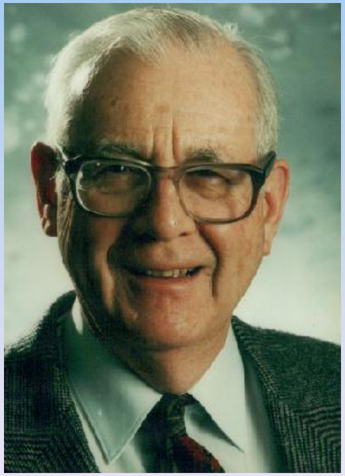
C.A.Coulomb
1736-1806

WJM Rankine
1820-1872

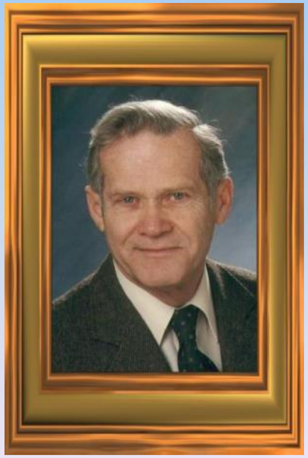
A.Casagrande
1902-1981

L. Bjerrum
1918-1973

A.W.Skempton
1914-



G.F.Sowers
1921-1996



G.A. Leonards
1921-1997

SOIL ELEMENTS

Degree of Saturation in %

$S=V_w/V_v$

Voids Ratio

$e=V_v/V_s$

Porosity in %

$n=V_v/V_t$

Water Content in %

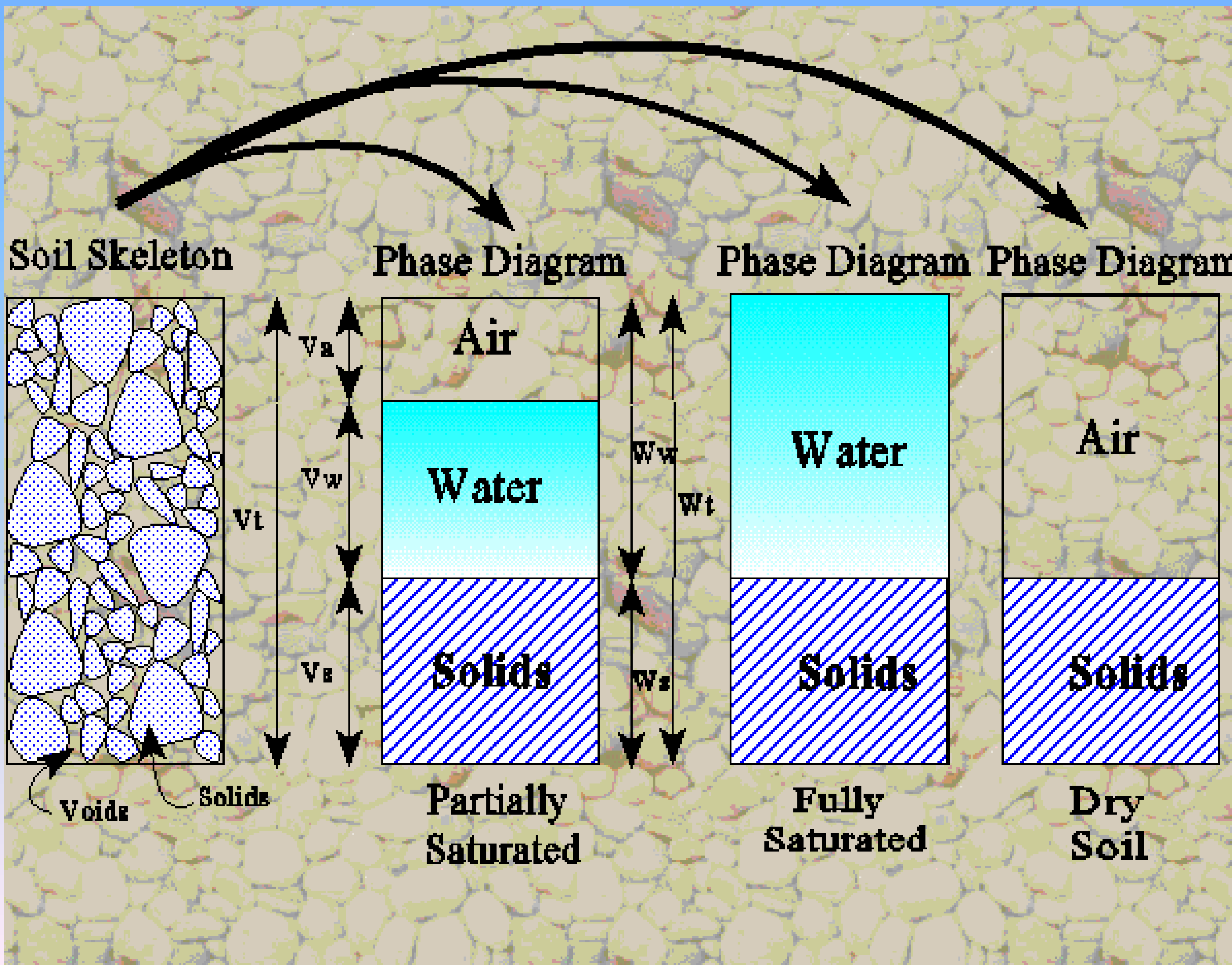
$w=W_w/W_s$

Bulk density gm/cc

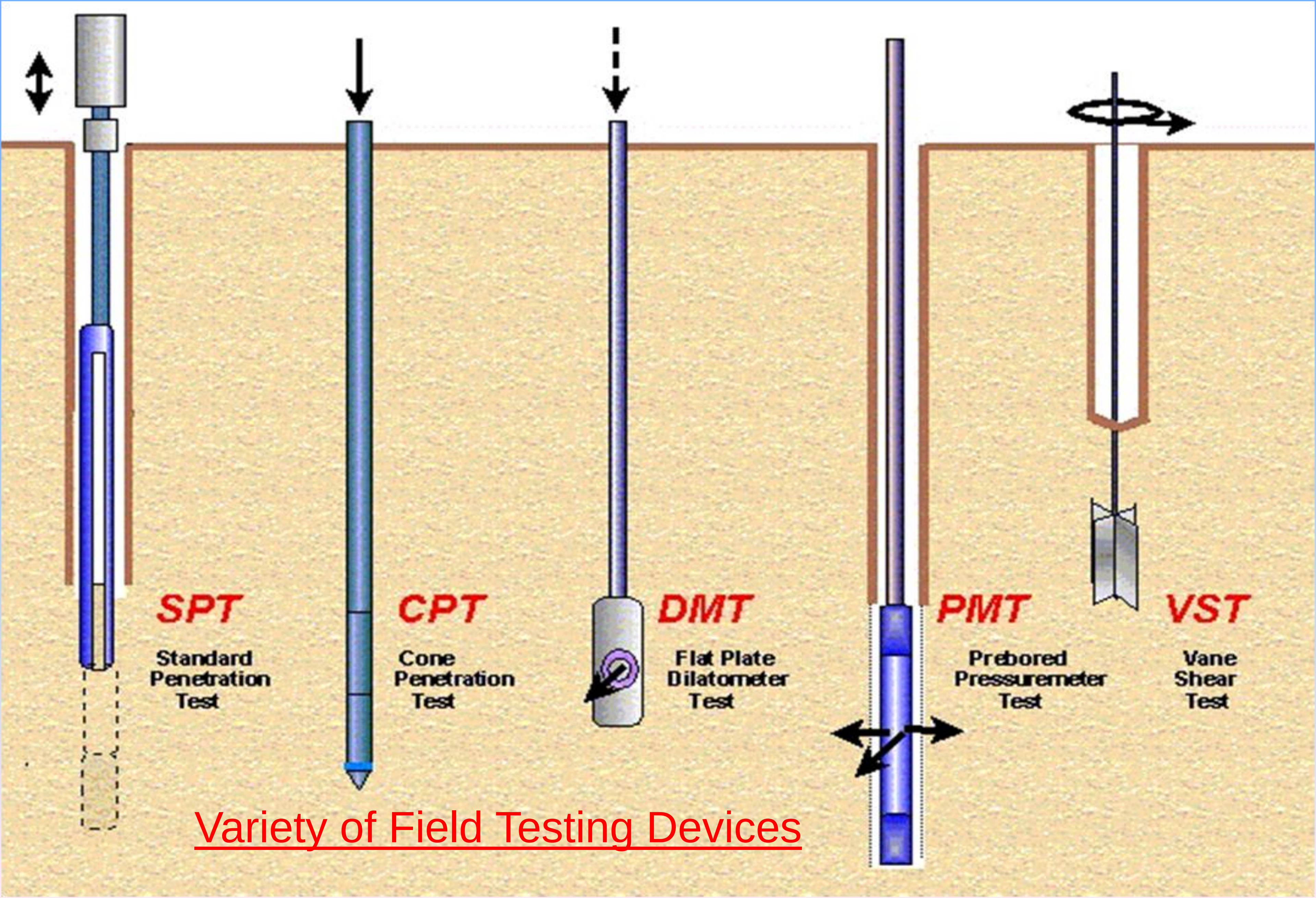
$\gamma=W/V_t$

Dry density gm/cc

$\gamma_d=W_s/V_t$



Soil Testing

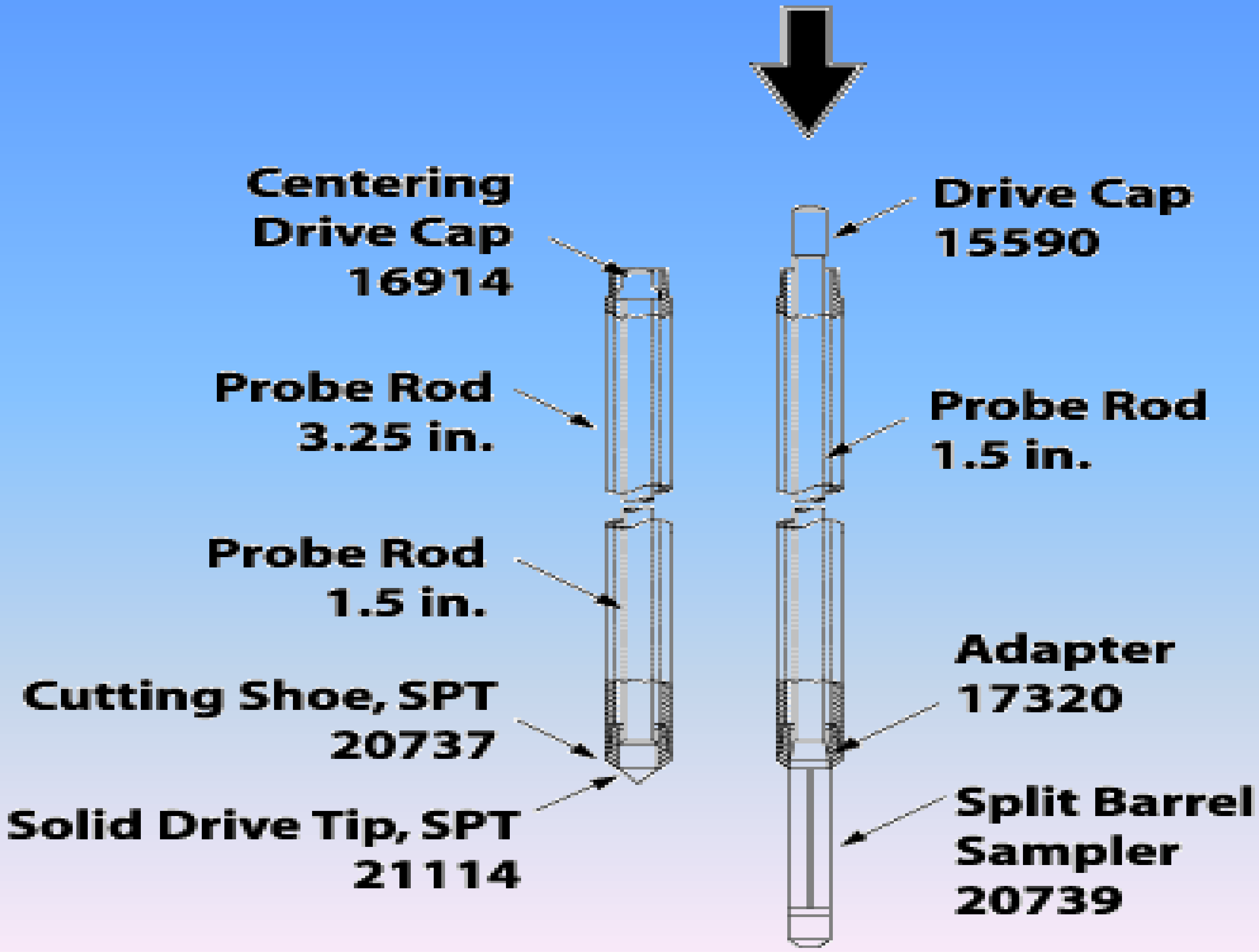


Variety of Field Testing Devices

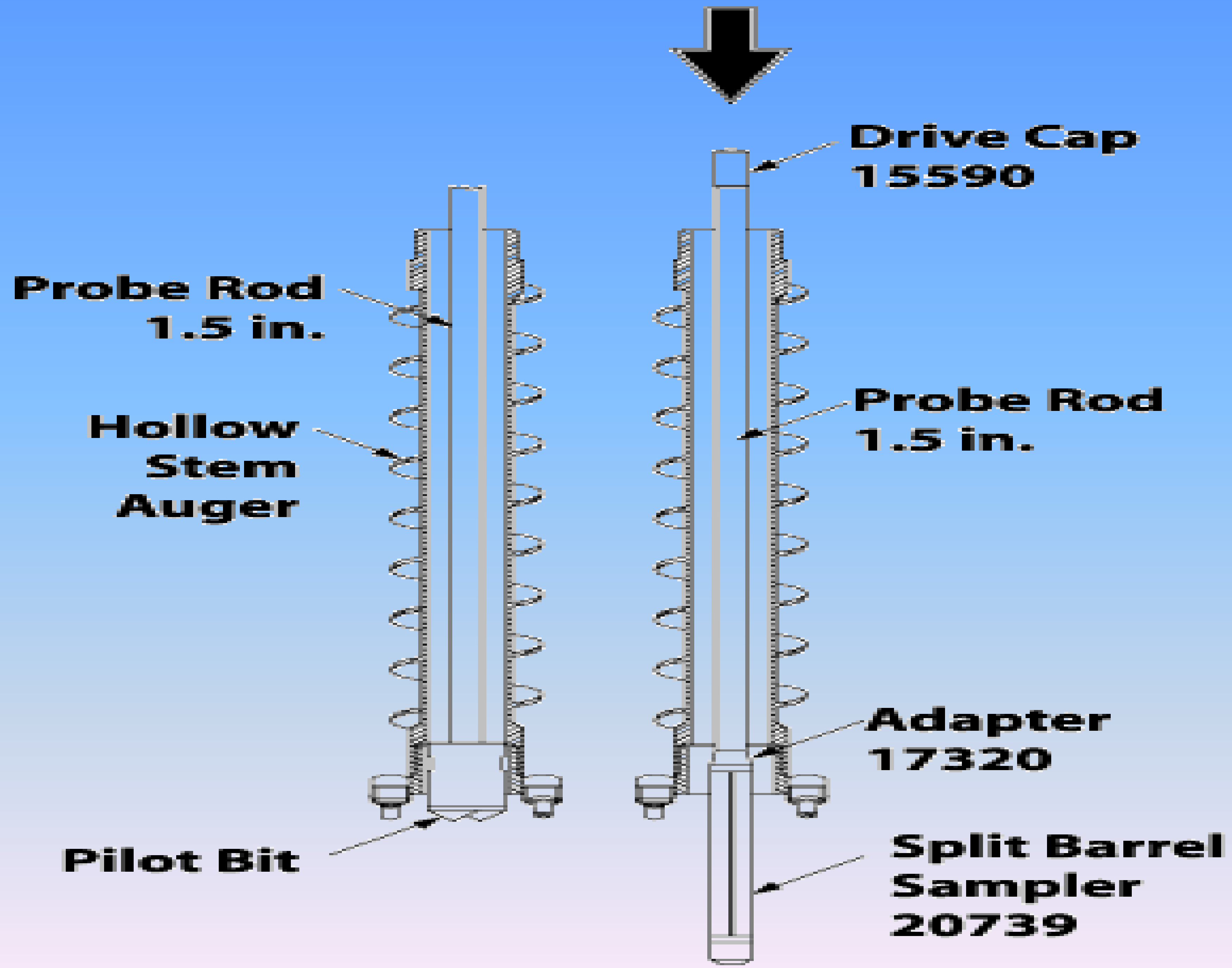
SPTآزمایش نفوذ استاندارد

Standard penetration test

1-Using a 140 lb. (64 kg) driving mass falling free from a height of 30 in. (762 mm)...
2-Driving the standard split spoon sampler a distance of 18 in. (457 mm) into the soil, and...
3-Counting the number of blows (N) to drive the sampler 12 in. (6 in. plus 6 in.) [152 mm plus 152 mm].



Centering Drive Cap 16914
Probe Rod 3.25 in.
Probe Rod 1.5 in.
Cutting Shoe, SPT 20737
Solid Drive Tip, SPT 21114
Drive Cap 15590
Probe Rod 1.5 in.
Adapter 17320
Split Barrel Sampler 20739



Drive Cap
15590
Probe Rod
1.5 in.
Hollow
Stem
Auger
Probe Rod
1.5 in.
Adapter
17320
Pilot Bit
Split Barrel
Sampler
20739

Moisture Content

- The moisture content, m, is defined as

$$m = \frac{Weight\ of\ Water}{Weight\ of\ Solids} = \frac{W_w}{W_s}$$

In terms of e, S, G_s and γ_w

$$W_w = \gamma_w V_w = \gamma_w e S V_s$$

$$W_s = \gamma_s V_s = \gamma_w G_s V_s$$

hence

$$m = \frac{e S}{G_s}$$

Example 1

- Distribution by mass and weight

Phase	Trimmings Mass (g)	Sample Mass, M (g)	Sample Weight, Mg (kN)
Total	55	290	2845×10^{-6}
Solid	45	237.3	2327.9×10^{-6}
Water	10	52.7	517×10^{-6}

- Distribution by volume (assume $G_s = 2.65$)

Total Volume $V = \pi r^2 l$

Water Volume $V_w = \dfrac{W_w}{\gamma_w}$

Solids Volume $V_s = \dfrac{W_s}{\gamma_w G_s}$

Air Volume $V_a = V - V_s - V_w$

Moisture content $m = \frac{W_w}{W_s} = \frac{10}{45} = 0.222 = 22.2\,\%$

Voids ratio $e = \frac{V_v}{V_s} = \frac{V_a + V_w}{V_s} = 0.755$

Degree of Saturation $S = \frac{V_w}{V_v} = \frac{V_w}{V_a + V_w} = 0.780 = 78.0\,\%$

Bulk unit weight $\gamma_{bulk} = \frac{W}{V} = 18.1\,kN/m^3$

Dry unit weight $\gamma_{dry} = \frac{W_s}{V} = 14.8\,kN/m^3$

Saturated unit weight $\gamma_{sat} = \frac{(W + 14.9 \times 10^{-6} \times 9.81)}{V} = 19.04\,kN/m^3$

Note that $\gamma_{dry} \le \gamma_{bulk} \le \gamma_{sat}$

Atterberg Limits

- Particle size is not that useful for fine grained soils

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- Particle size is not that useful for fine grained soils

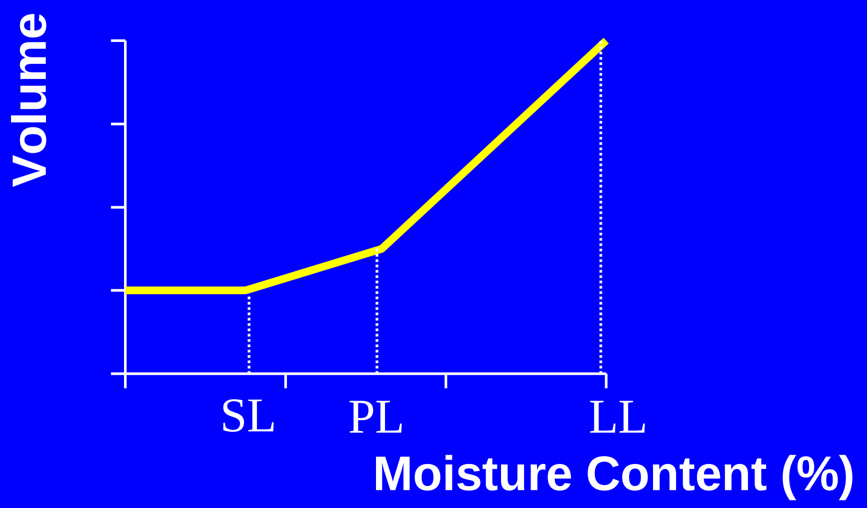

Figure 4 Moisture content versus volume relation during drying

Atterberg Limits

- Particle size is not that useful for fine grained soils

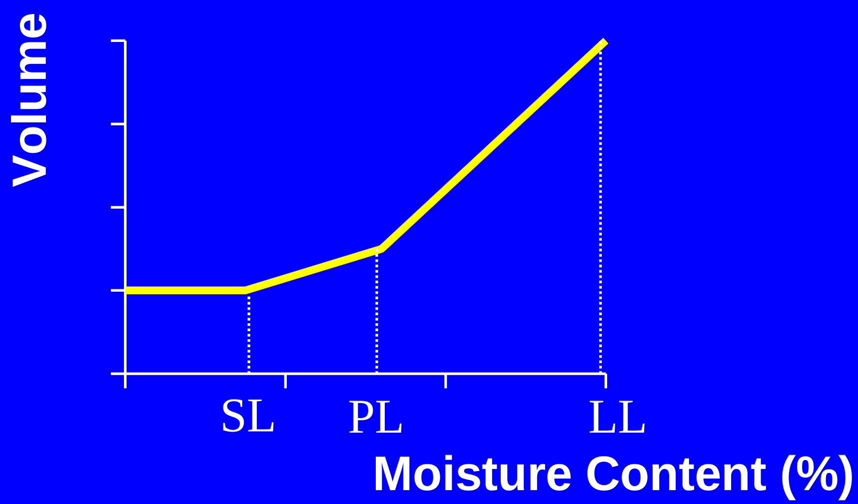

Figure 4 Moisture content versus volume relation during drying

- SL - Shrinkage Limit
- PL - Plastic Limit
- LL - Liquid limit

Atterberg Limits

SL - Shrinkage Limit

PL - Plastic Limit

LL - Liquid limit

$$\text{Moisture content} = \frac{\text{mass of water}}{\text{mass of solids}}$$

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Plasticity Index = LL - PL = PI or I_p

Atterberg Limits

SL - Shrinkage Limit

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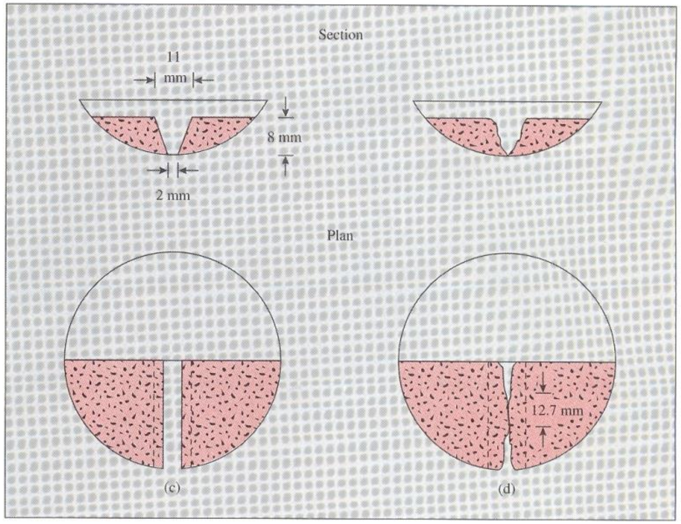
$$\text{Moisture content} = \frac{\text{mass of water}}{\text{mass of solids}}$$

Plasticity Index = LL - PL = PI or I_p

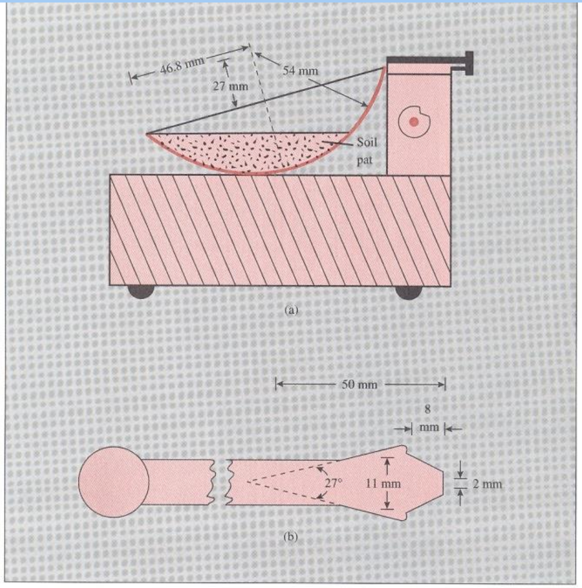
Liquidity Index = (m - PL)/I_p = LI

LIQUID LIMIT - ATTERBERG'S LIMITS

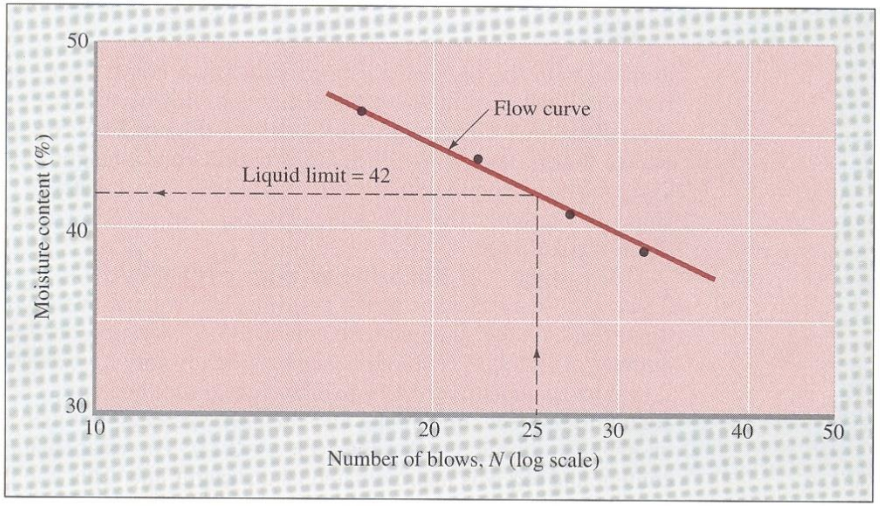
<u>Liquid Limit</u> is the water content at which 25 blows cause the groove to close.



▼ FIGURE 2.9 (Continued)



▼ FIGURE 2.9 Liquid limit test: (a) liquid limit device; (b) grooving tool; (c) soil pat before test; (d) soil pat after test

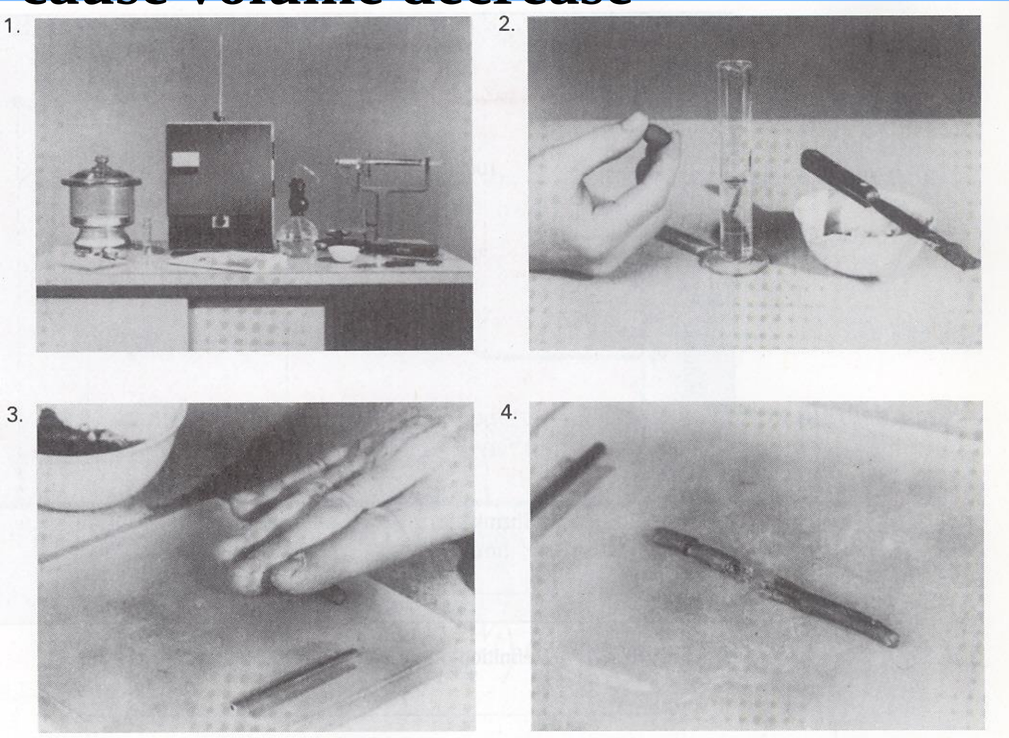


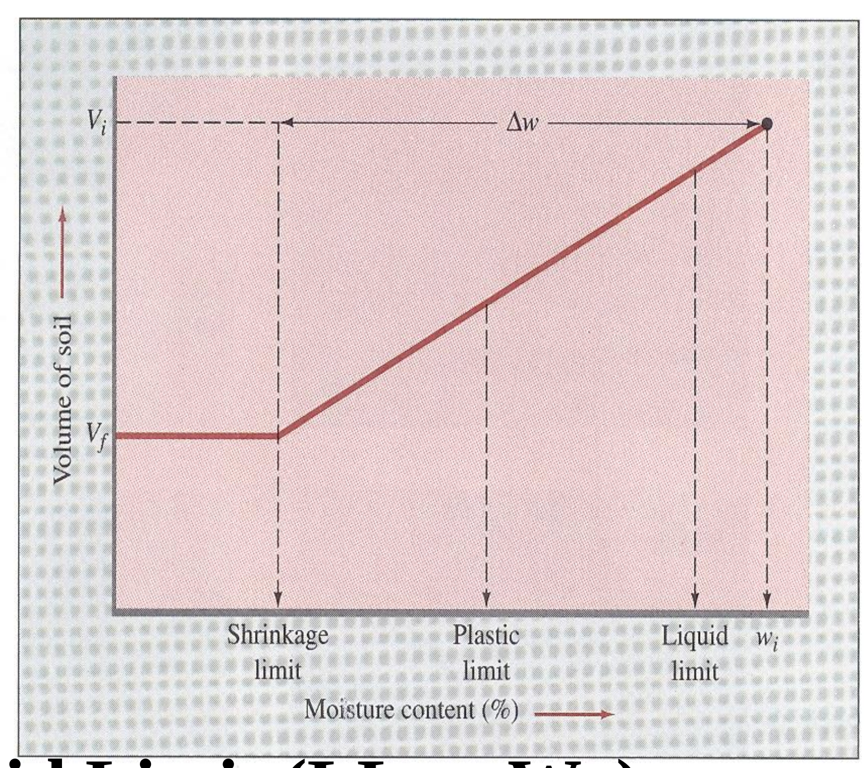
▼ FIGURE 2.11 Flow curve for liquid limit determination of a clayey silt

PLASTIC & SHRINKAGE LIMIT

Plastic Limit is water content at which 3 mm diameter roller of soil starts crumbling

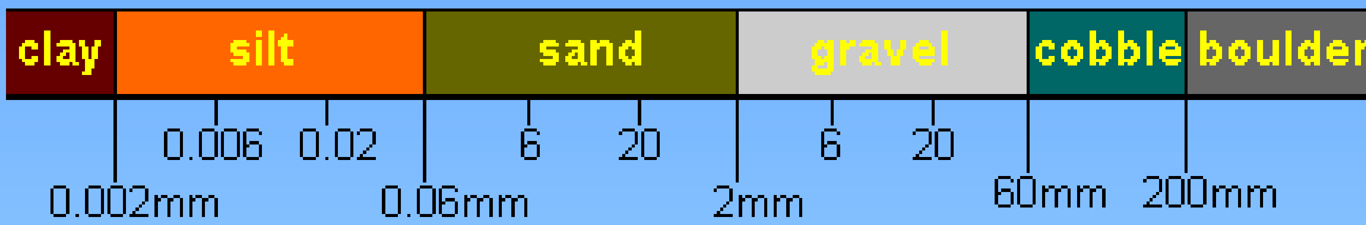
Shrinkage Limit is water content beyond reduction which does not cause volume decrease



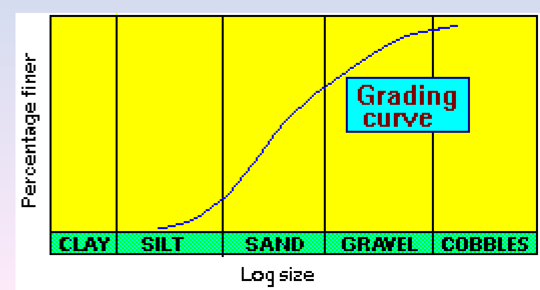


Plasticity Index PI or I_P = Liquid Limit (LL or W_L) – Plastic Limit (PL or W_P)

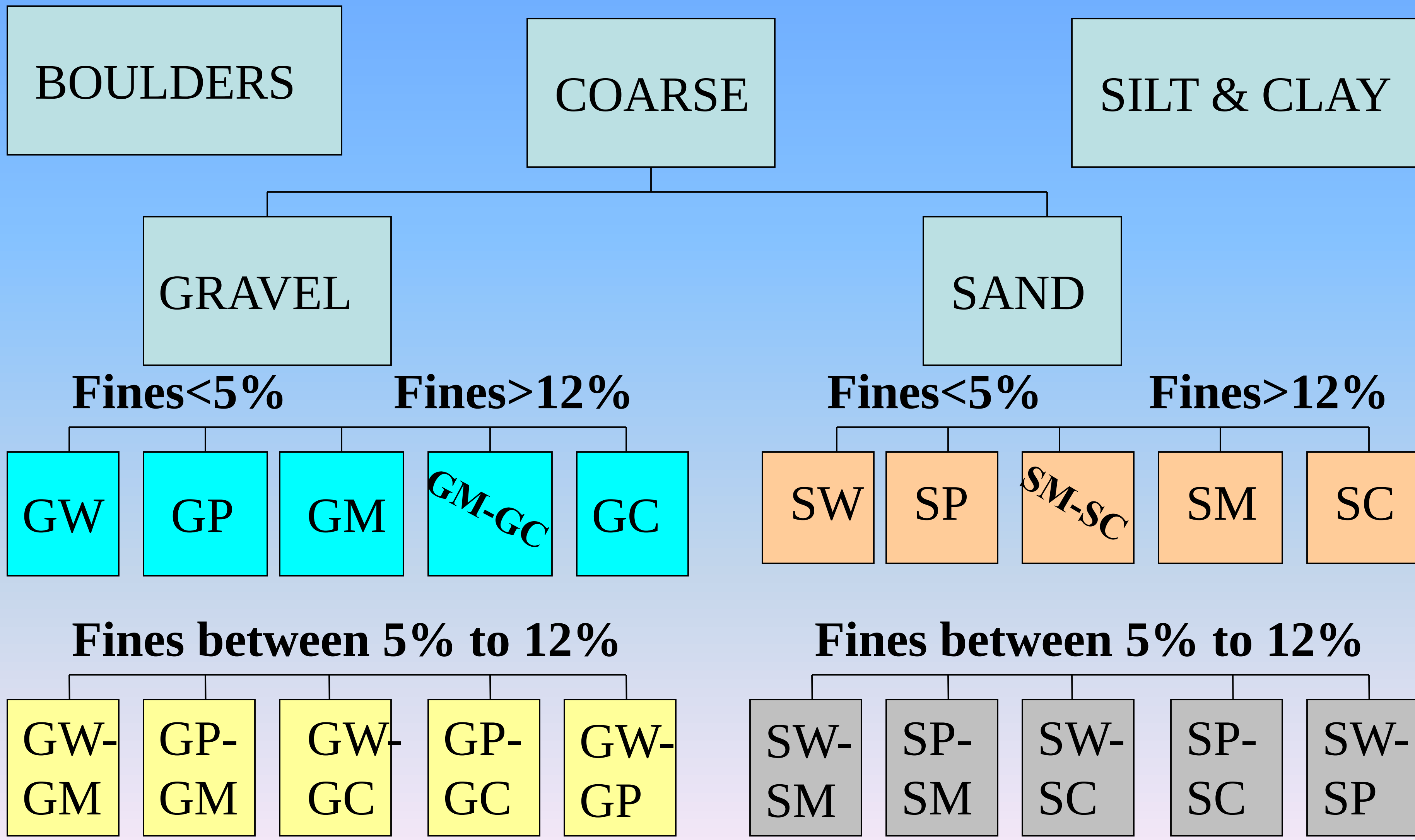
Aggregates(سنگدانه ها)



Very coarse soils	BOULDERS		> 200 mm
	COBBLES		60 - 200 mm
Coarse soils	**G** GRAVEL	coarse	20 - 60 mm
		medium	6 - 20 mm
		fine	2 - 6 mm
	S SAND	coarse	0.6 - 2.0 mm
		medium	0.2 - 0.6 mm
		fine	0.06 - 0.2 mm
Fine soils	**M** SILT	coarse	0.02 - 0.06 mm
		medium	0.006 - 0.02 mm
		fine	0.002 - 0.006 mm
	C CLAY		< 0.002 mm



CLASSIFICATION IS:1498 - 1970



Sieve analysis

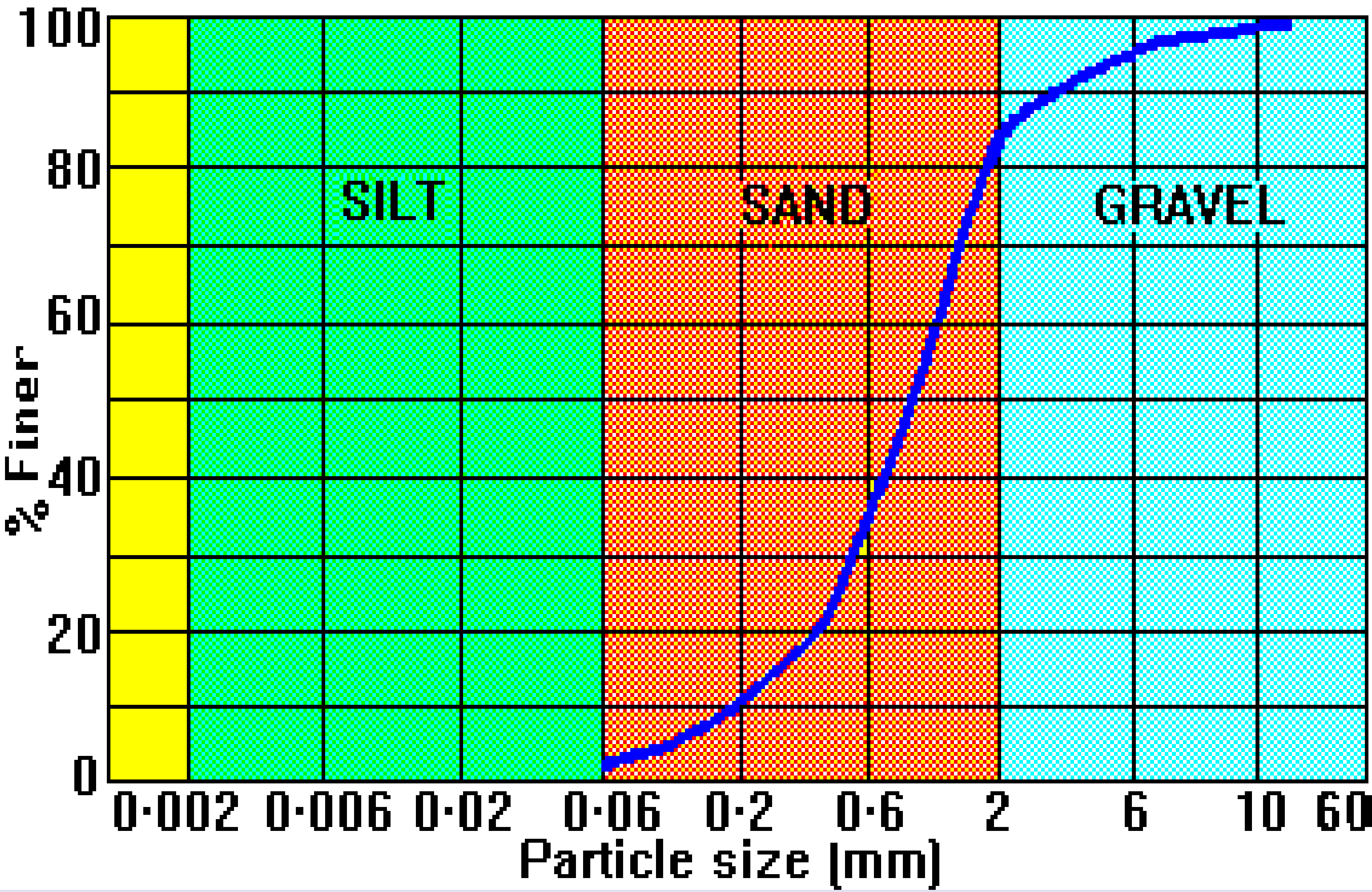
(Grading)

Sieve Analysis Apparatus: A) Sieve aperture sizes, B) Dry oven, C) Sieve shaker, D) Mortar & Tray, E) Rubber pestle, [F] Balance

Sieve analysis example

The results of a dry-sieving test are given below, together with the grading analysis and grading curve. Note carefully how the tabulated results are set out and calculated. The grading curve has been plotted on special semi-logarithmic paper; you can also do this analysis using a spreadsheet.

Sieve mesh size (mm)	Mass retained (g)	Percentage retained	Percentage finer (passing)
14.0	0	0	100.0
10.0	3.5	1.2	98.8
6.3	7.6	2.6	86.2
5.0	7.0	2.4	93.8
3.35	14.3	4.9	88.9
2.0	21.1	7.2	81.7
1.18	56.7	19.4	62.3
0.600	73.4	25.1	37.2
0.425	22.2	7.6	29.6
0.300	26.9	9.2	20.4
0.212	18.4	6.3	14.1
0.150	15.2	5.2	8.9
0.063	17.5	6.0	2.9
Pan	**8.5**	**2.9**	
TOTAL	**292.3**	**100.0**	



The soil comprises: 18% gravel, 45% coarse sand, 24% medium sand, 10% fine sand, 3% silt, and is classified therefore as: a **well-graded gravelly SAND**

By Method 1:

Sieve Sizes (mm)	Mass Retained (g)	Percentage Retained (g)	Percentage Passing (%)
1.18	0	0	100
0.600	20	(20/500)x100 = 4	100-4 = 96
0.300	170	(170/500)x100 = 34	96-34 = 62
0.150	235	(235/500)x100 = 47	62-47 = 15
0.063	71	(71/500)x100 = 14.2	15-14.2 = 0.8
Pan	3.5	Check: (3.5/500)x100 = 0.7 %	

By Method 2:

Sieve Sizes (mm)	Mass Retained (g)	Cumulative Mass Passing (g)	Percentage Passing (%)
1.18	0	500-0 = 500	100
0.600	20	500-20 = 480	(480/500)x100 = 96
0.300	170	480-170 = 310	(310/500)x100 = 62
0.150	235	310-235 = 75	(75/500)x100 = 15
0.063	71	75-71 = 4	(4/500)x100 = 0.8
Pan	3.5	4-3.5 = 0.5	(0.5/500)x100 = 0.1

Calculation Formula:

Weight of dried soil sample (initial sample mass), $W_{total} = 500$ g

Percentage Retained = (Mass Retained / W_{total}) x 100 %

Sieve Opening (mm)	Mass of Soil Retained, M_n	Percent of Mass Retained, R_n	Cumulative Percent Retained, $\sum R_n$	Percent Finer, 100 - $\sum R_n$ (%)
4.75	154	(154/822)x100 = 18.7	18.7	100-18.7 = 81.3
2.36	72	(72/822)x100 = 8.7	18.7+8.7 = 27.4	100-27.4 = 72.6
1.18	72	(72/822)x100 = 8.7	27.4+8.7 = 36.1	100-36.1 = 63.9
0.60	141	(141/822)x100 = 17.1	36.1+71.1 = 53.2	100-53.2 = 46.8
0.425	85	(85/822)x100 = 10.3	53.2+10.3 = 63.5	100-63.5 = 36.5
0.30	80	(80/822)x100 = 9.7	63.5+9.7 = 73.2	100-73.2 = 26.8
0.15	149	(149/822)x100 = 18.1	73.2+18.1 = 91.3	100-91.3 = 8.7
0.075	45	(45/822)x100 = 5.5	91.3+5.5 = 96.8	100-96.8 = 3.2
Pan	24	(24/822)x100 = 2.9	96.8+2.9 = 99.7	-

Calculation Formula:

Weight of dried soil sample, W_{total} = 824 g

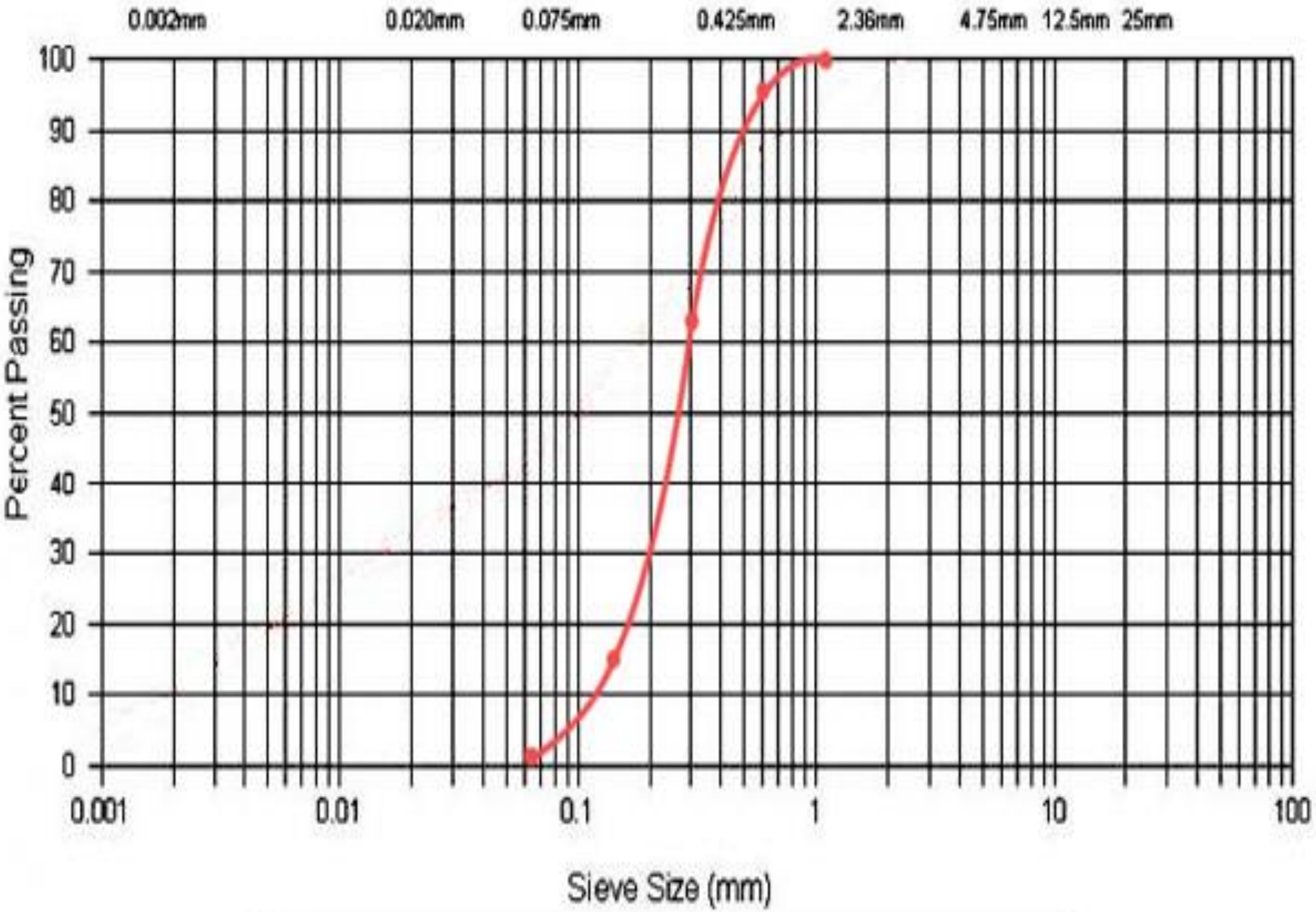
Percent of Mass Retained, $R_n = (M_n / W_1) \times 100\ \%$

Total Mass of Soil Retained, $\sum M_n = W_1 = (154+72+72+141+85+80+149+45+24) = 822$ g

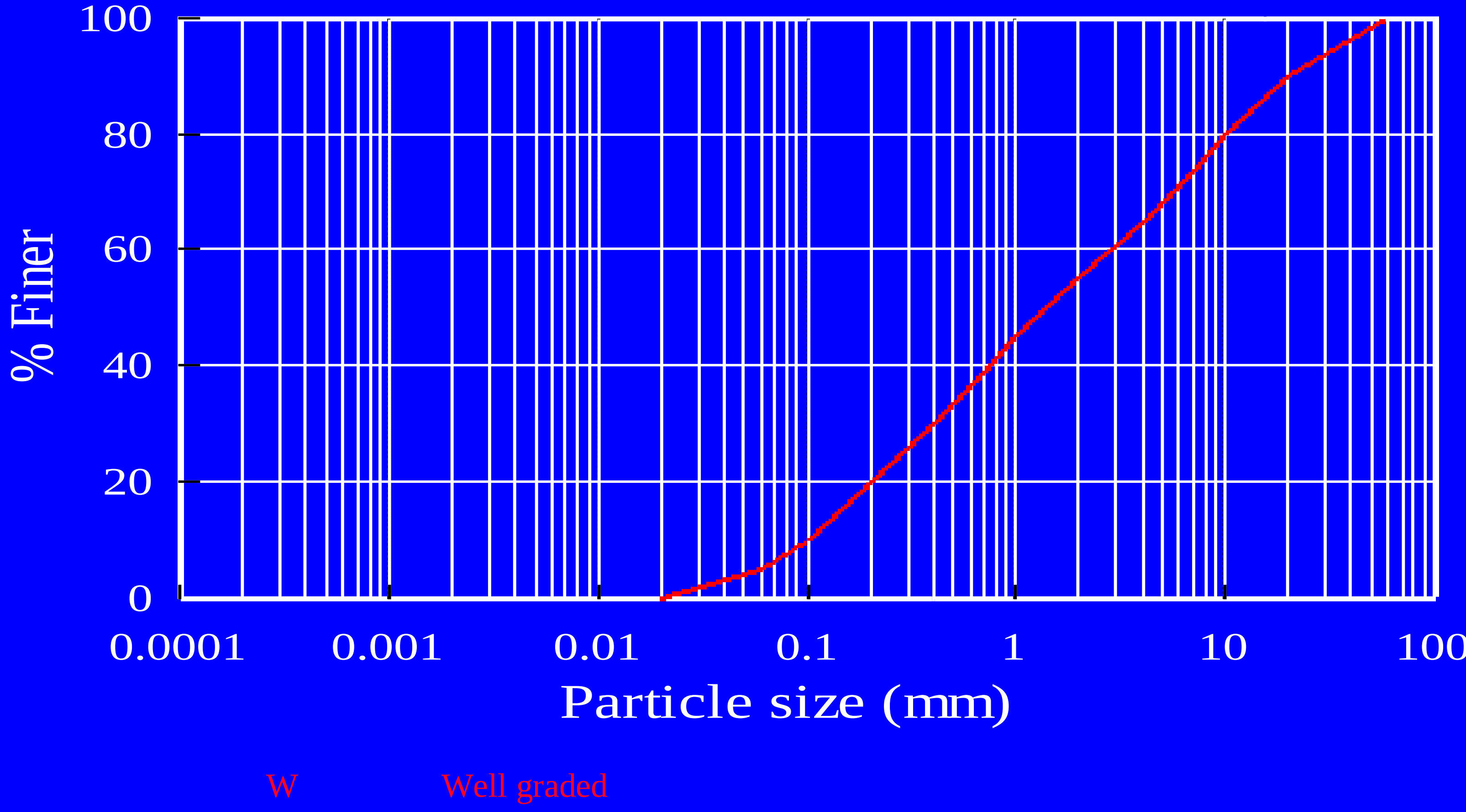
Mass Loss during Sieve Analysis; $[(W_{total} - W_1) / W_{total}] \times 100\ \% = [(824 - 822) / 824 = 0.2\ \%$

Note: OK if < 2 %

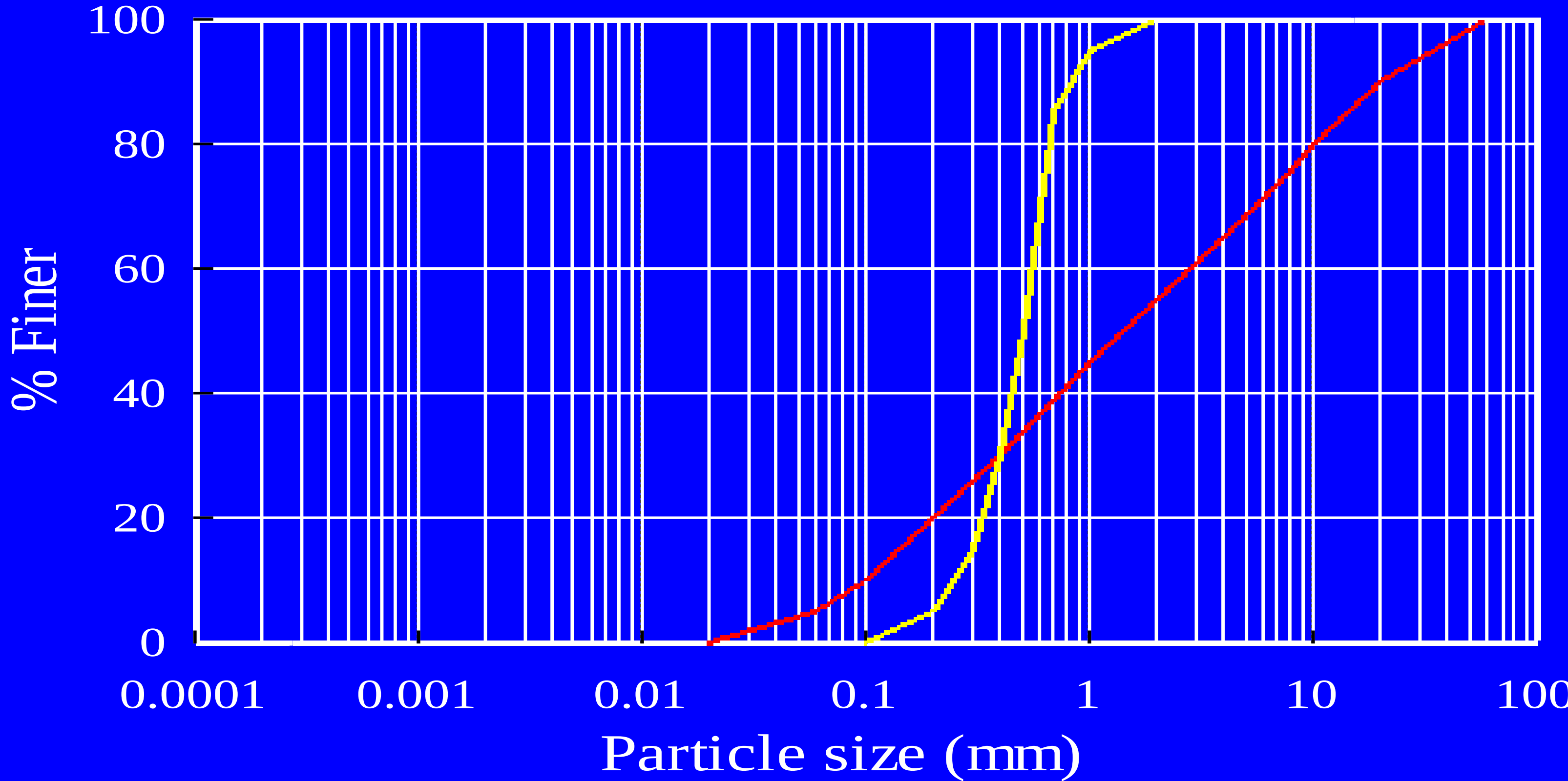
The Graphs


0.002mm
0.020mm
0.075mm
0.425mm
2.36mm
4.75mm
12.5mm
25mm
Percent Passing
100
90
80
70
60
50
40
30
20
10
0
0.001
0.01
0.1
1
10
100
Sieve Size (mm)

Grading curves



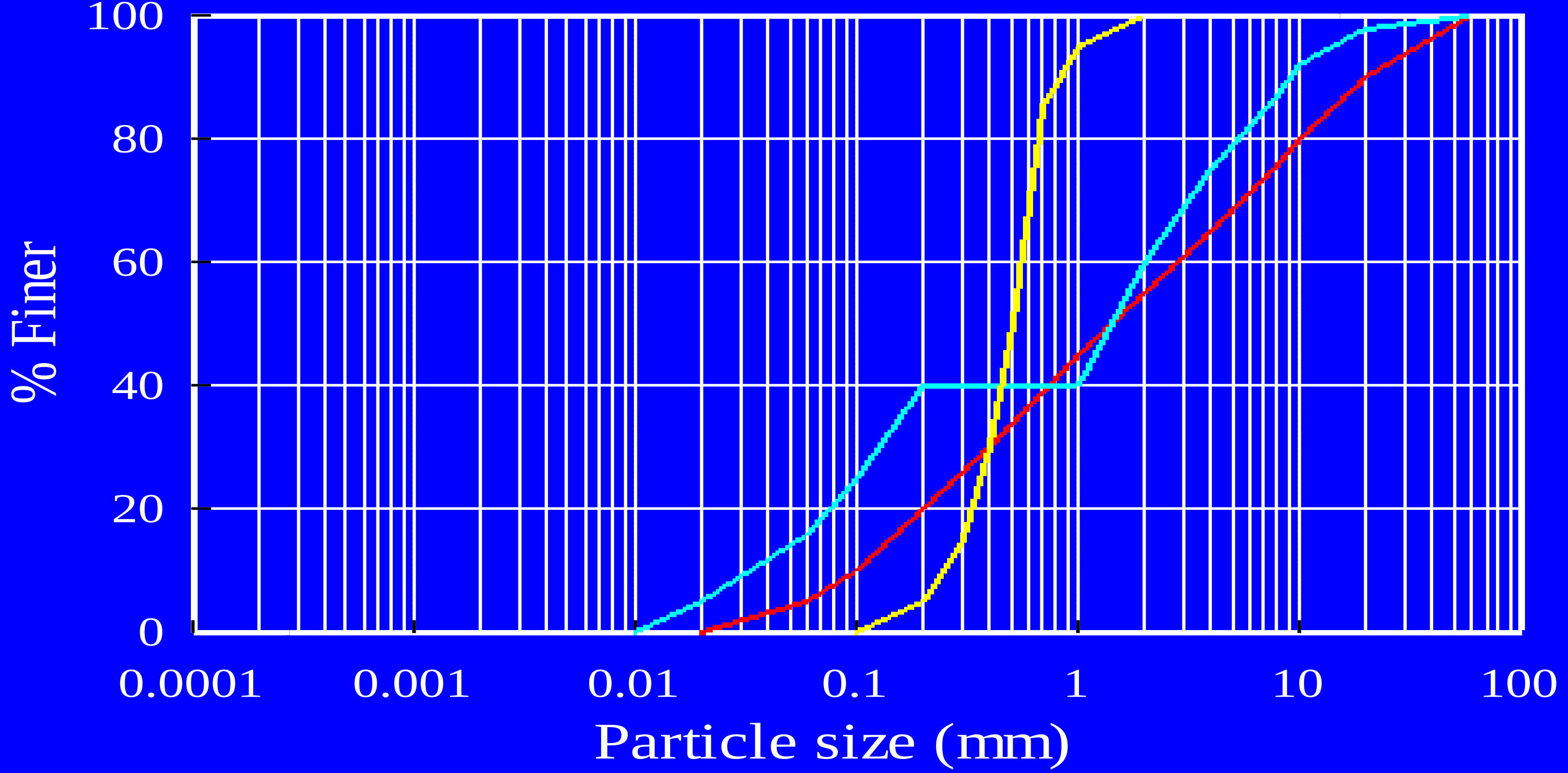
Grading curves



W Well graded

U Uniform

Grading curves

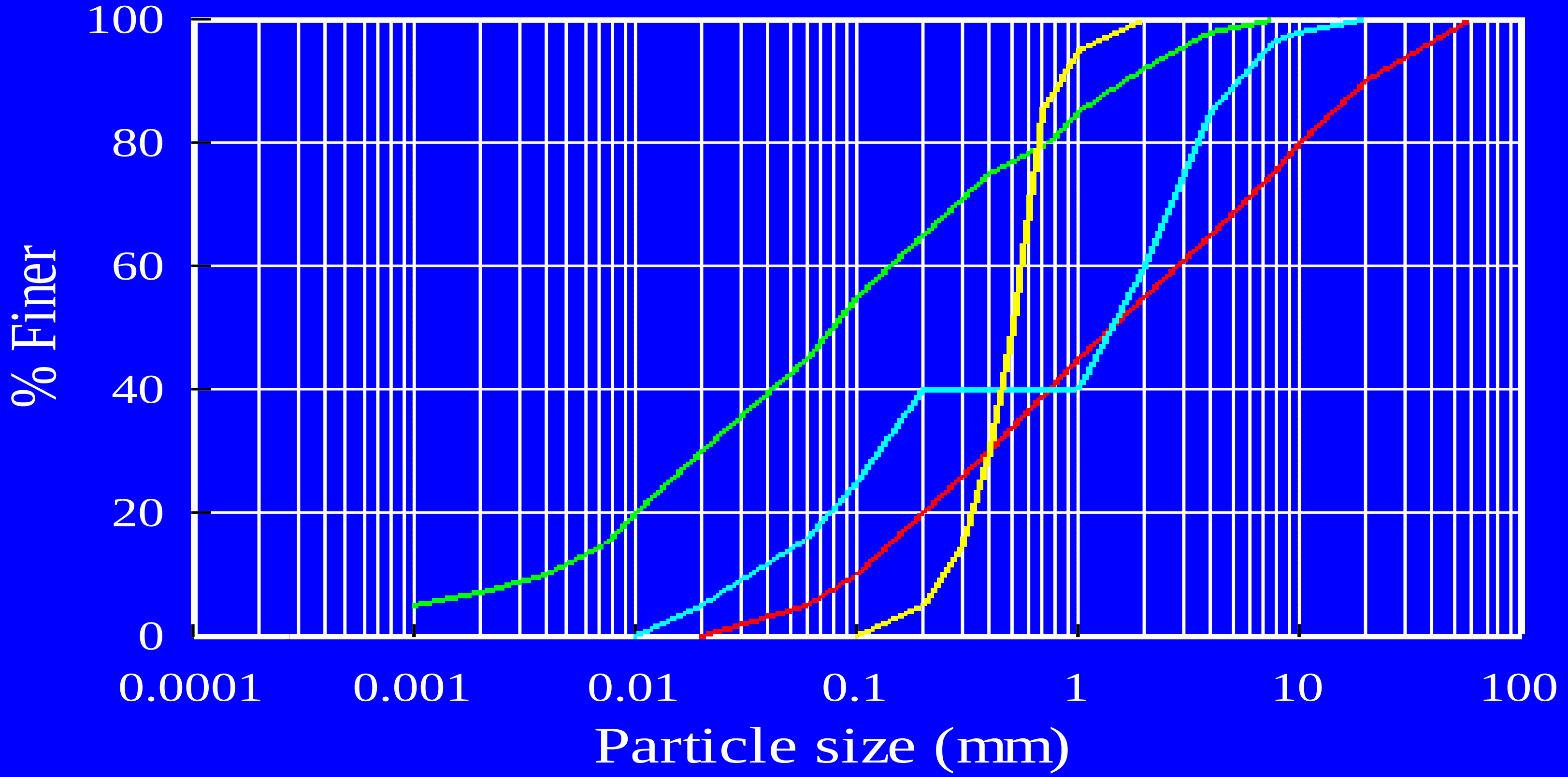


W Well graded

U Uniform

P Poorly graded

Grading curves



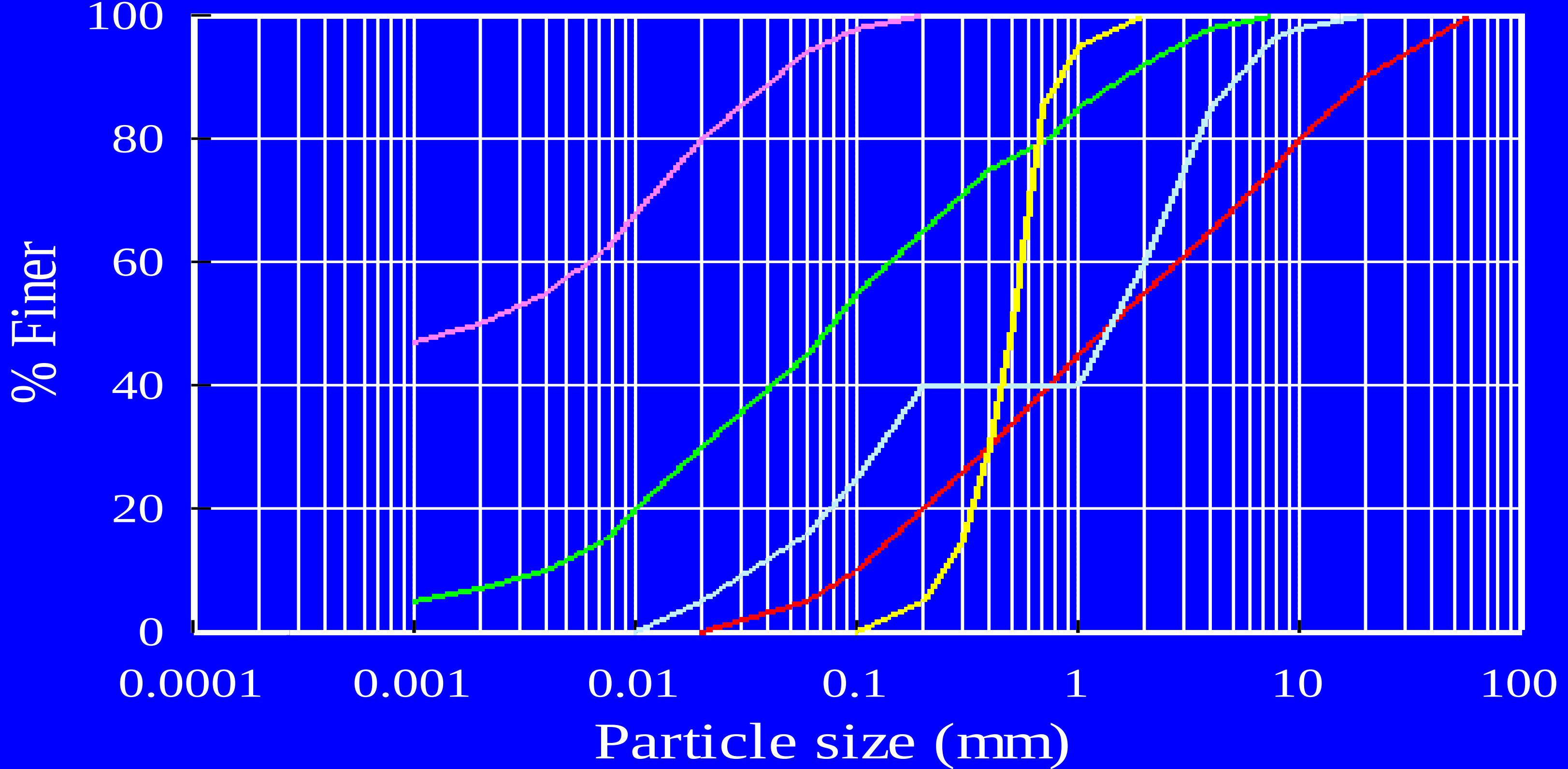
W Well graded

U Uniform

P Poorly graded

C Well graded with some clay

Grading curves



W Well graded

U Uniform

P Poorly graded

C Well graded with some clay

F Well graded with an excess of fines

Unified Soil Classification

To determine if W or P, calculate C_u and C_c

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

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

x% of the soil has particles smaller than D_x

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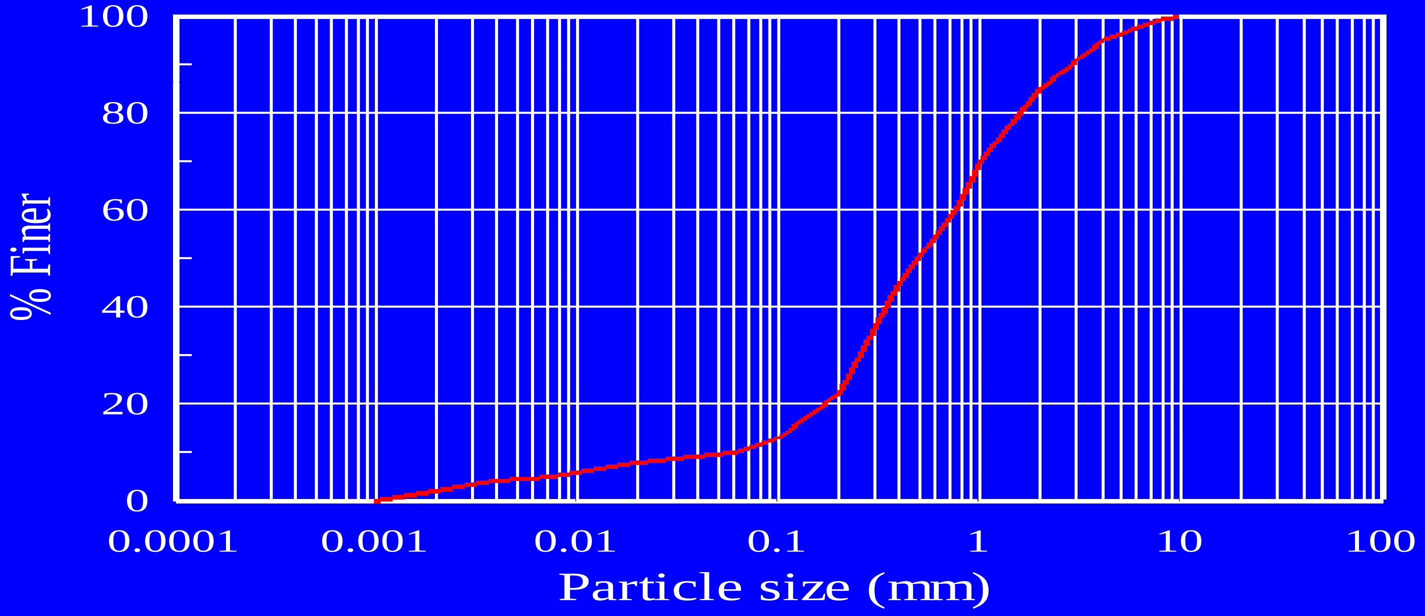

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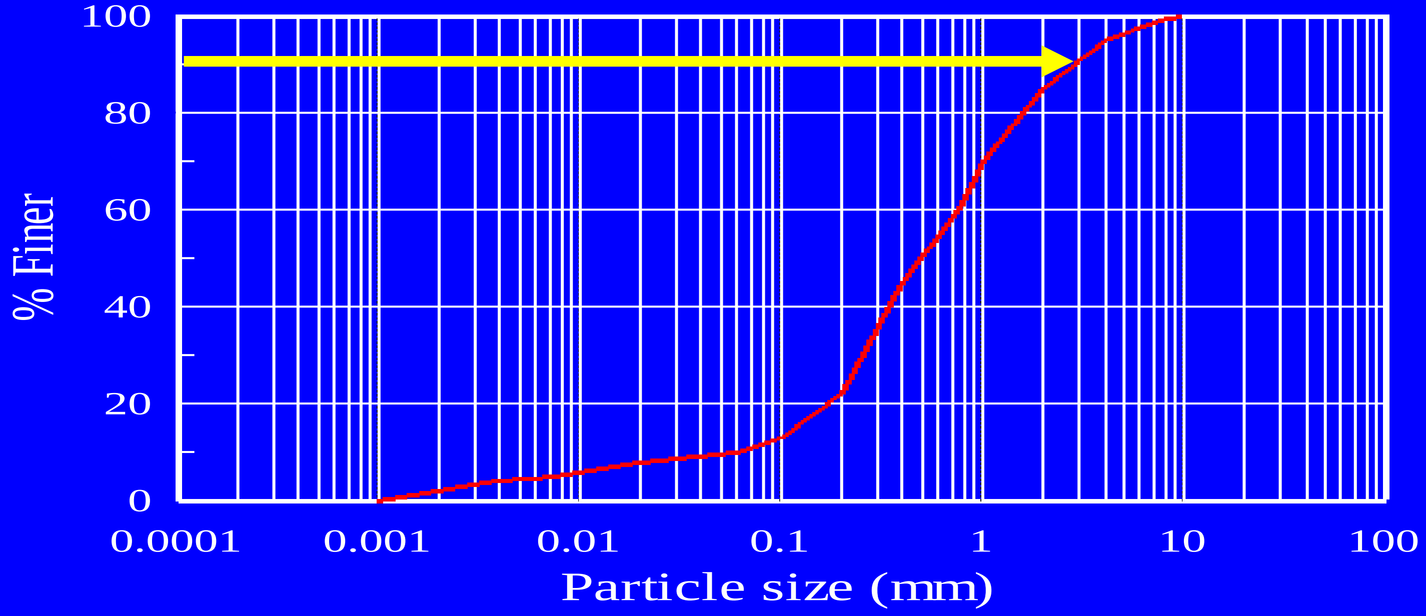

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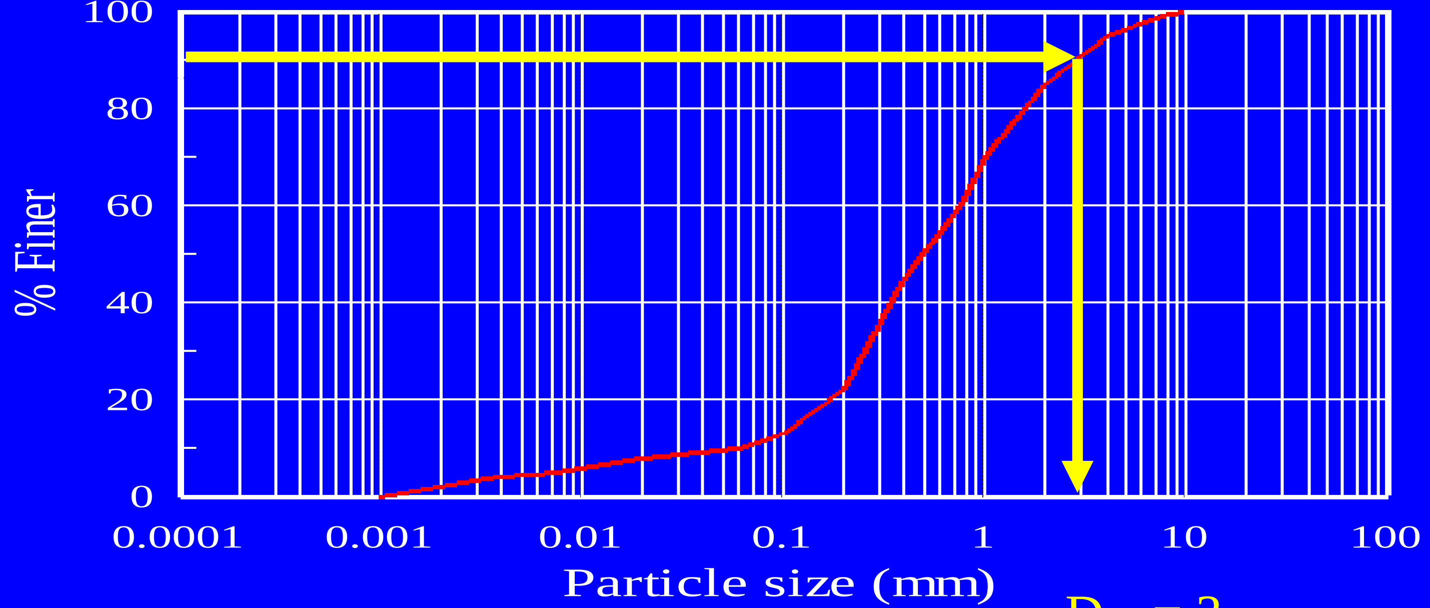


D_{90} = 3 mm

Unified Soil Classification

To determine W or P, calculate C_u and C_c

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

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

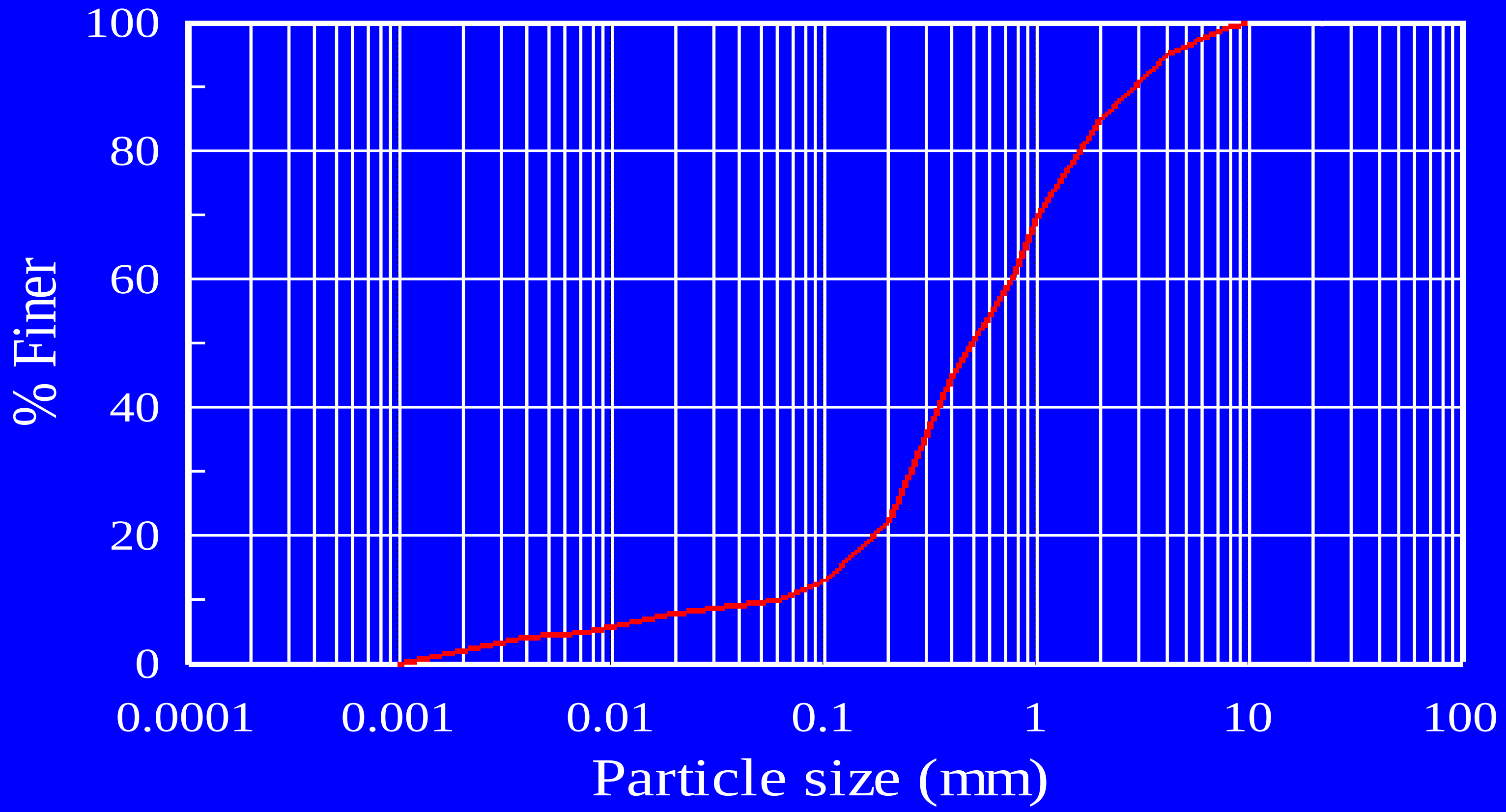
If prefix is G then suffix is W if $C_u > 4$ and C_c is between 1 and 3

otherwise use P

If prefix is S then suffix is W if $C_u > 6$ and C_c is between 1 and 3

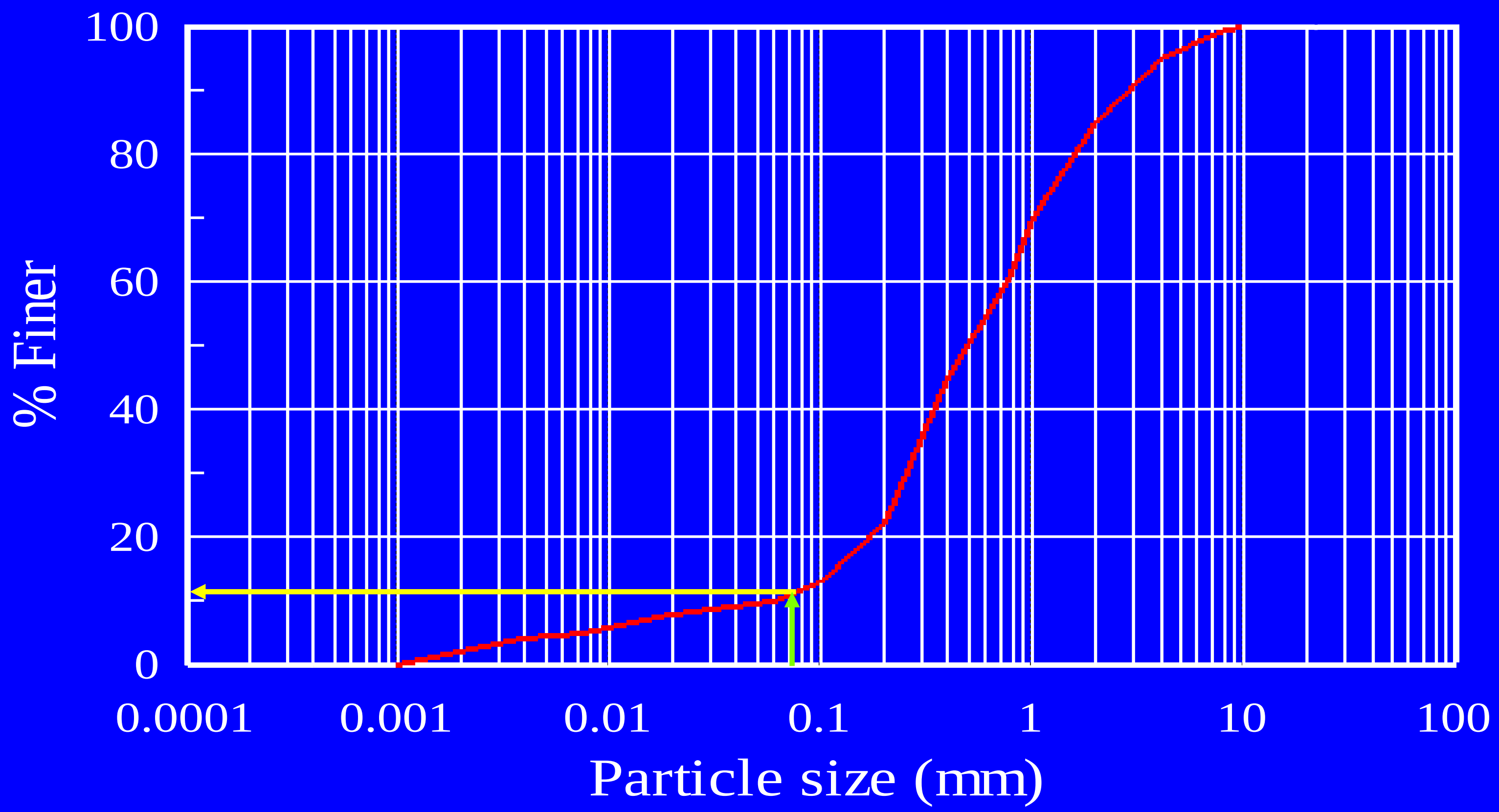
otherwise use P

Example



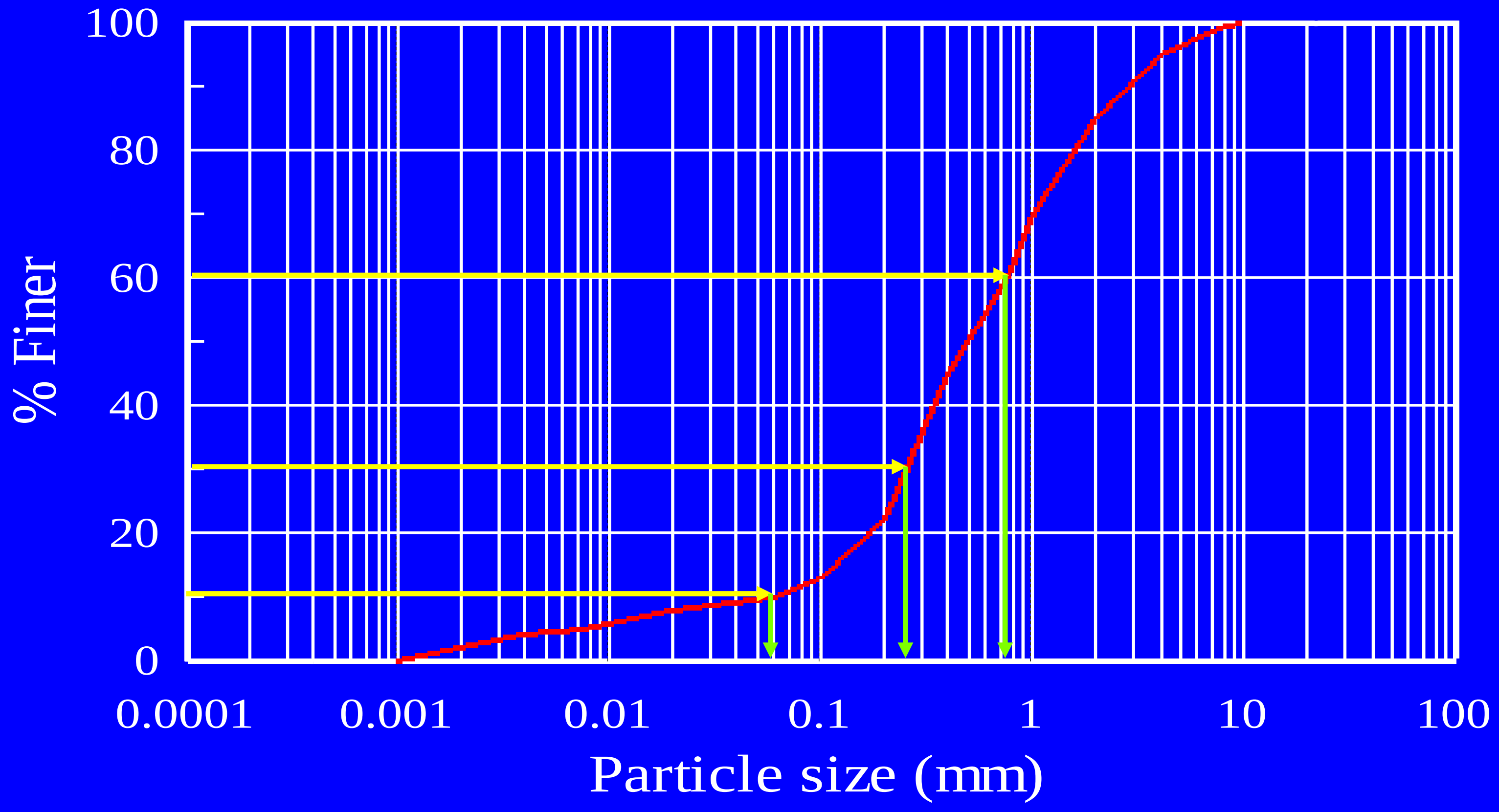
100
80
60
40
20
0
% Finer
0.0001
0.001
0.01
0.1
1
10
100
Particle size (mm)

Example



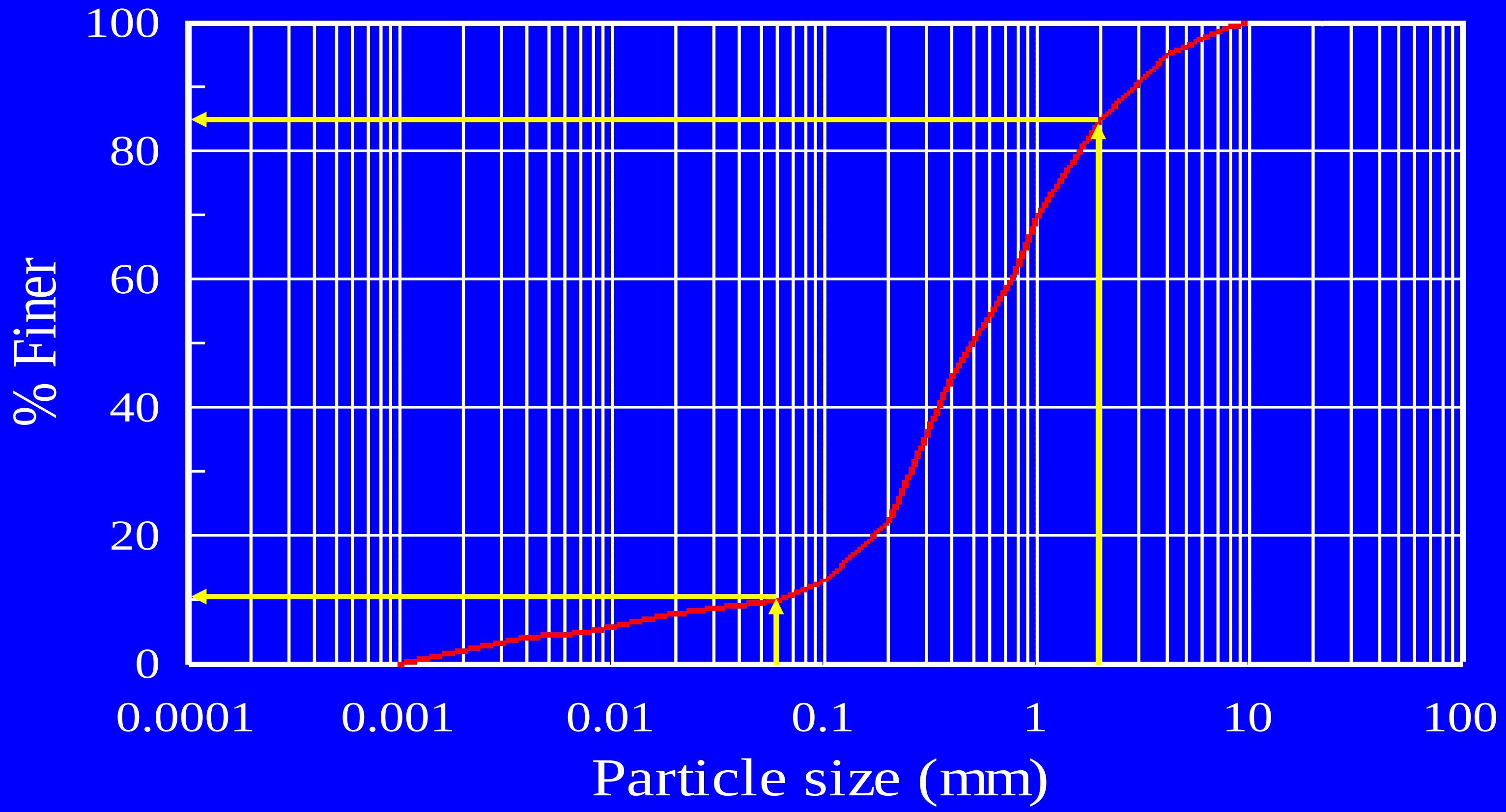
- %fines (% finer than 75 μm) = 11% - Dual symbols required

Example



- %fines (% finer than 75 μm) = 11% - Dual symbols required
- D_{10} = 0.06 mm, D_{30} = 0.25 mm, D_{60} = 0.75 mm

Example



Particle size fractions: Gravel 17%

Sand 73%

Silt and Clay 10%

Sieves


Compaction

Purposes of Compaction

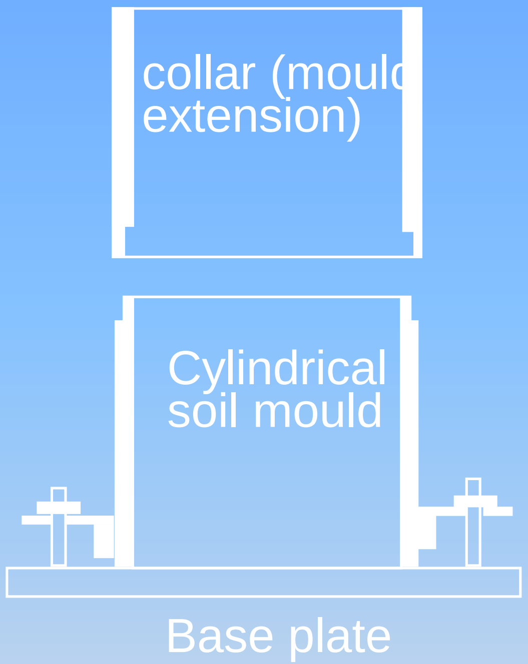
- Compaction is the application of energy to soil to reduce the void ratio
  - This is usually required for fill materials, and is sometimes used for natural soils
- Compaction reduces settlements under working loads
- Compaction increases the soil strength
- Compaction makes water flow through soil more difficult
- Compaction can prevent liquefaction during earthquakes

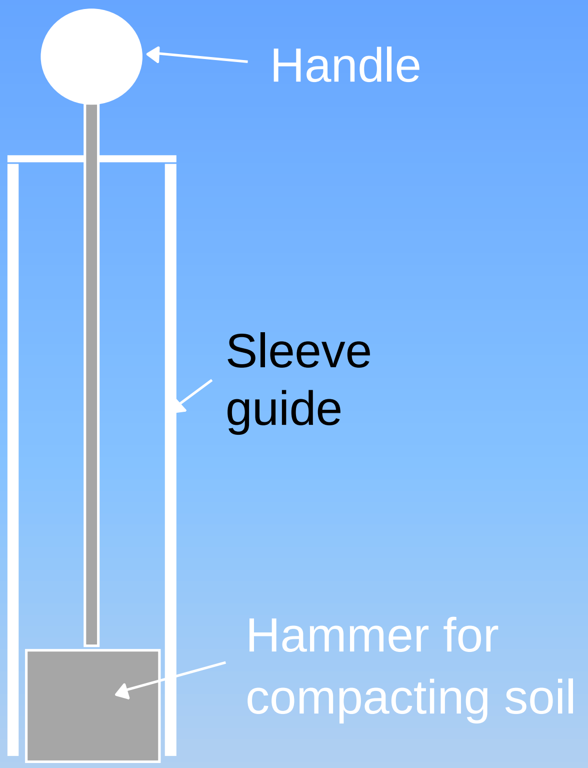
Factors affecting Compaction

- Water content of soil
- The type of soil being compacted
- The amount of compactive energy used

Laboratory Compaction tests

- Equipment





Laboratory Compaction tests

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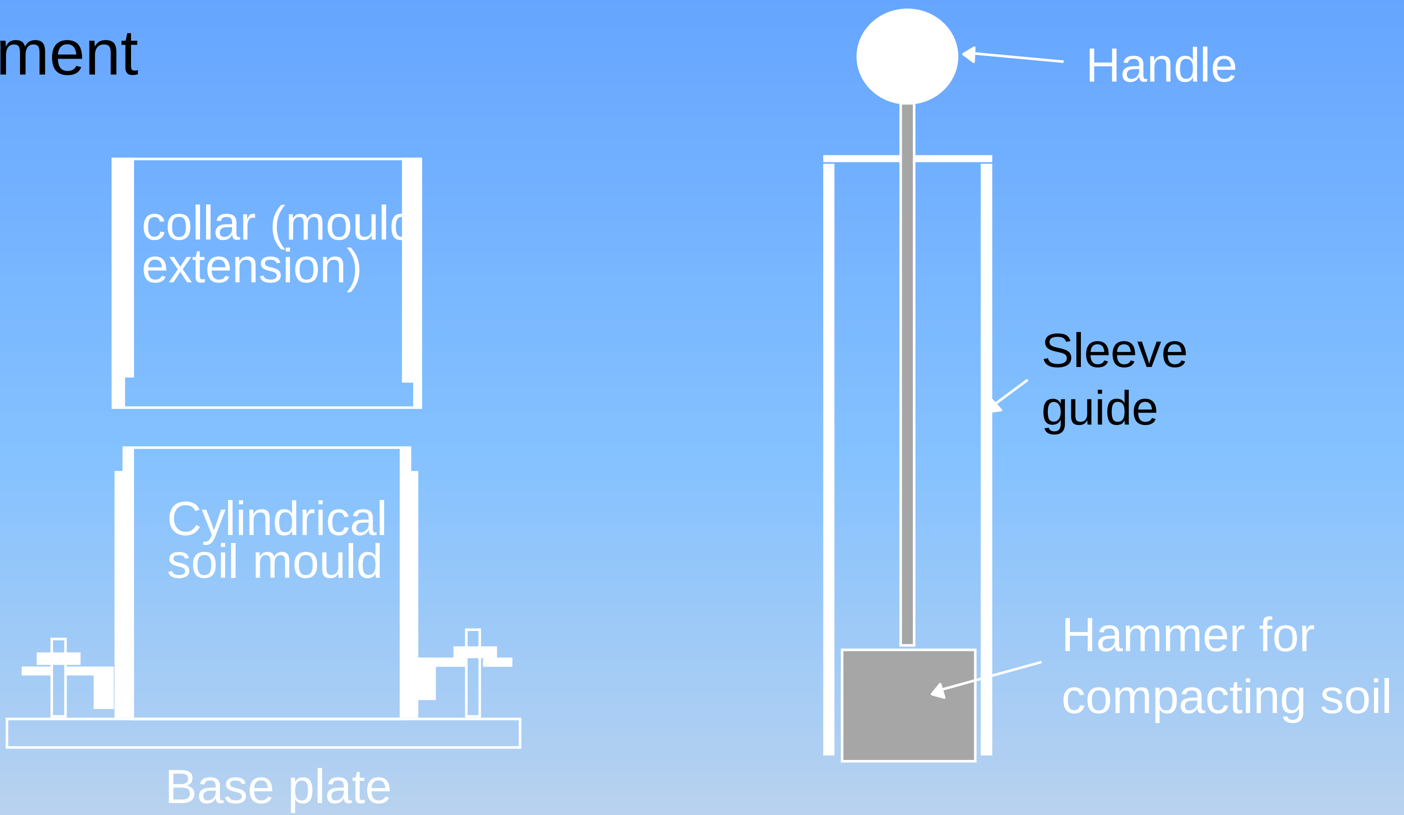

	Mould volume	Hammer mass	Hammer drop
Standard	1000	2.5	300
Modified	1000	4.9	450

Presentation of results

- The object of compaction is to reduce the void ratio, or to increase the dry unit weight.

$$\gamma_{dry} = \frac{G_s \gamma_w}{1 + e}$$

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$$\gamma_{dry} = \frac{G_s \gamma_w}{1 + e}$$

- In a compaction test bulk unit weight and moisture content are measured. The dry unit weight may be determined as follows

$$\gamma_{bulk} = \frac{W}{V} = \frac{Wt\ of\ Solids + Wt\ of\ Water}{Total\ Volume} = \frac{W_s + W_w}{V}$$

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$$\gamma_{bulk} = \frac{W}{V} = \frac{Wt\,of\ Solids + Wt\,of\ Water}{Total\,Volume} = \frac{W_s + W_w}{V}$$

$$\gamma_{bulk} = \frac{\left(1 + \frac{W_w}{W_s}\right) W_s}{V}$$

Presentation of results

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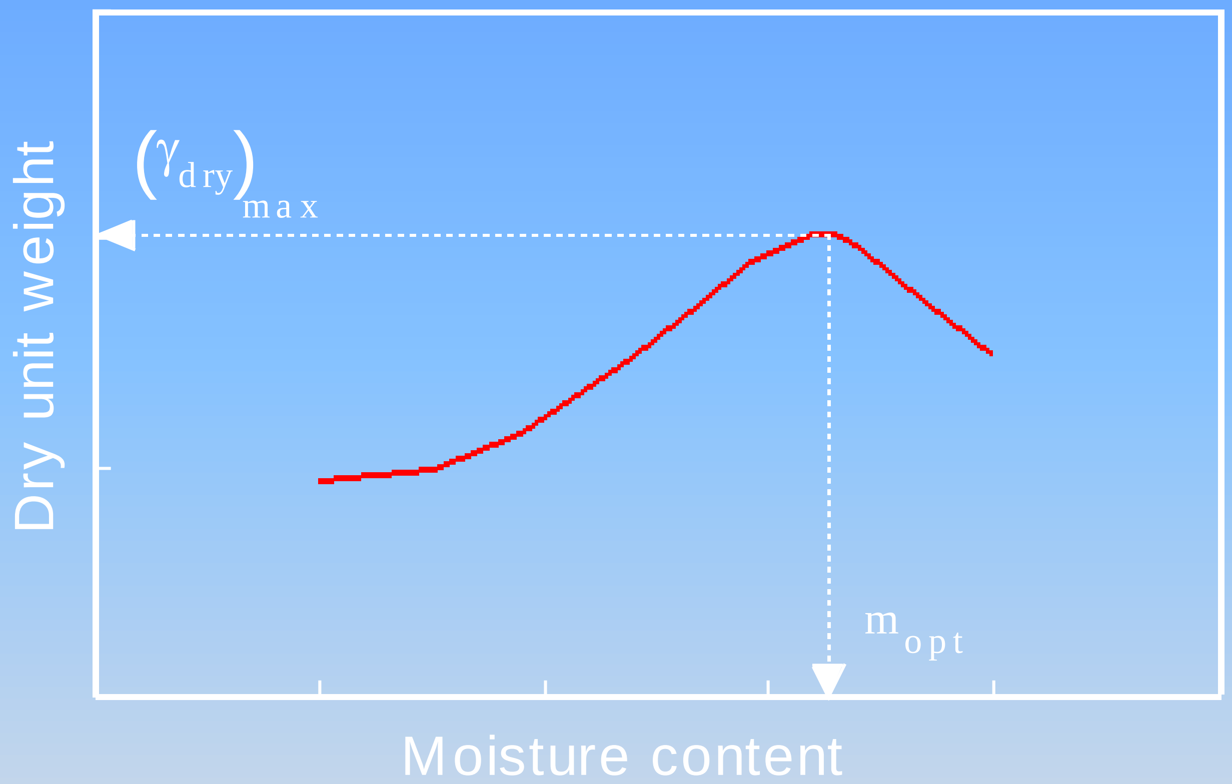
$$\gamma_{dry} = \frac{G_s \gamma_w}{1 + e}$$

- In a compaction test bulk unit weight and moisture content are measured. The dry unit weight may be determined as follows

$$\gamma_{bulk} = \frac{W}{V} = \frac{Wt\ of\ Solids + Wt\ of\ Water}{Total\ Volume} = \frac{W_s + W_w}{V}$$

$$\gamma_{bulk} = \frac{\left(1 + \frac{W_w}{W_s}\right) W_s}{V} = (1 + m)\gamma_{dry}$$

Presentation of Results



From the graph we determine the optimum moisture content, m_{opt} that gives the maximum dry unit weight, $(\gamma_{dry})_{max}$.

Presentation of results

- To understand the shape of the curve it is helpful to develop relations between γ_{dry} and the percentage of air voids, A.

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$$\gamma_{dry} = \frac{\gamma_{bulk}}{1 + m} = \frac{W_s + W_w}{V(1 + m)} = \frac{(W_s + W_w)(1 - \frac{A}{100})}{(V_s + V_w)(1 + m)}$$

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$$\gamma_{dry} = (1 - \frac{A}{100})\left[\frac{G_s \gamma_w}{G_s m + 1}\right]$$

Presentation of results

If the soil is saturated (A = 0) and

$$\gamma_{dry} = \left[\frac{G_s \gamma_w}{G_s m + 1} \right]$$

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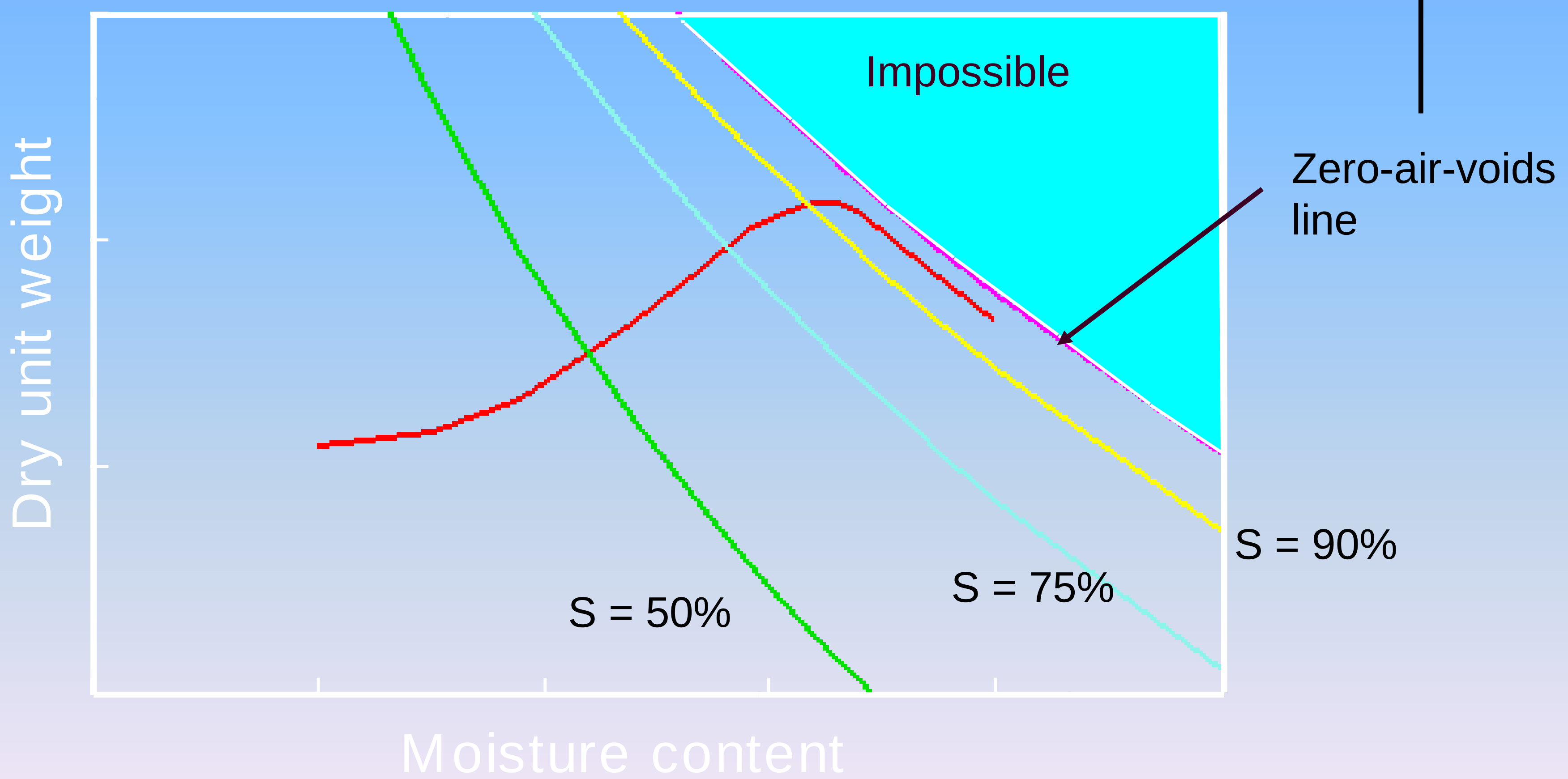


Effects of water content

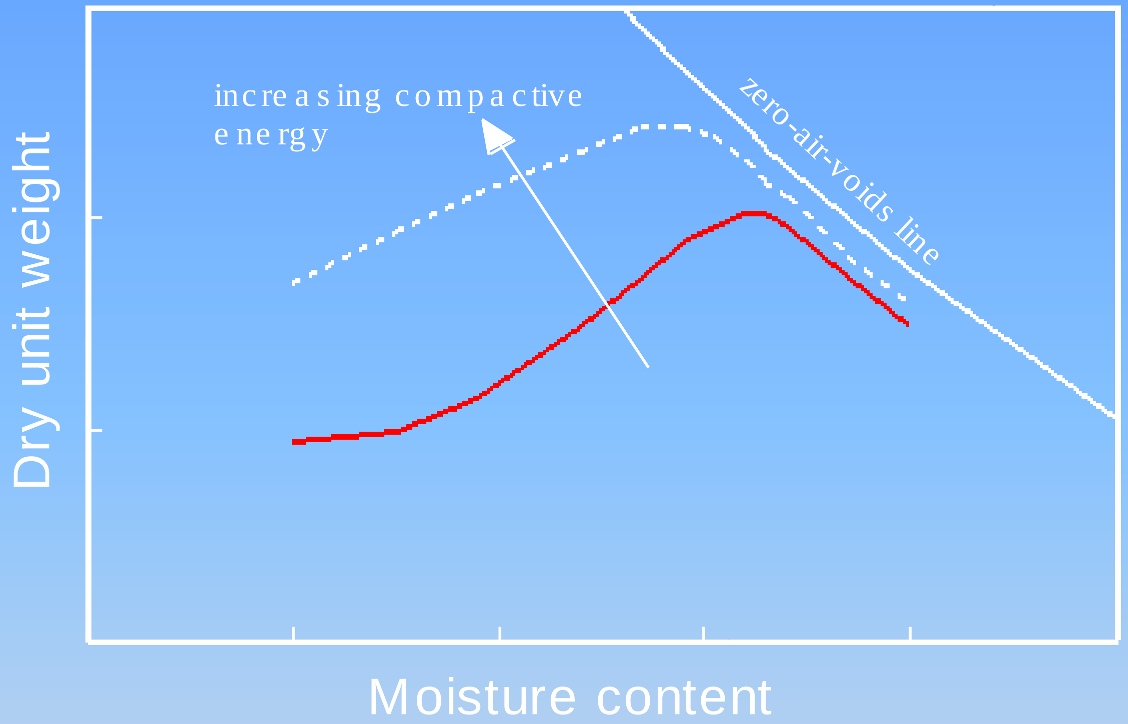
- Adding water at low moisture contents makes it easier for particles to move during compaction, and attain a lower void ratio. As a result increasing moisture content is associated with increasing dry unit weight.

- As moisture content increases, the air content decreases and the soil approaches the zero-air-voids line.

- The soil reaches a maximum dry unit weight at the optimum moisture content

- Because of the shape of the no-air-voids line further increases in moisture content have to result in a reduction in dry unit weight.

Effects of varying compactive effort



- Increasing energy results in an increased maximum dry unit weight at a lower optimum moisture content.
- There is no unique curve. The compaction curve depends on the energy applied.
- Use of more energy beyond m_{opt} has little effect.

Effects of soil type

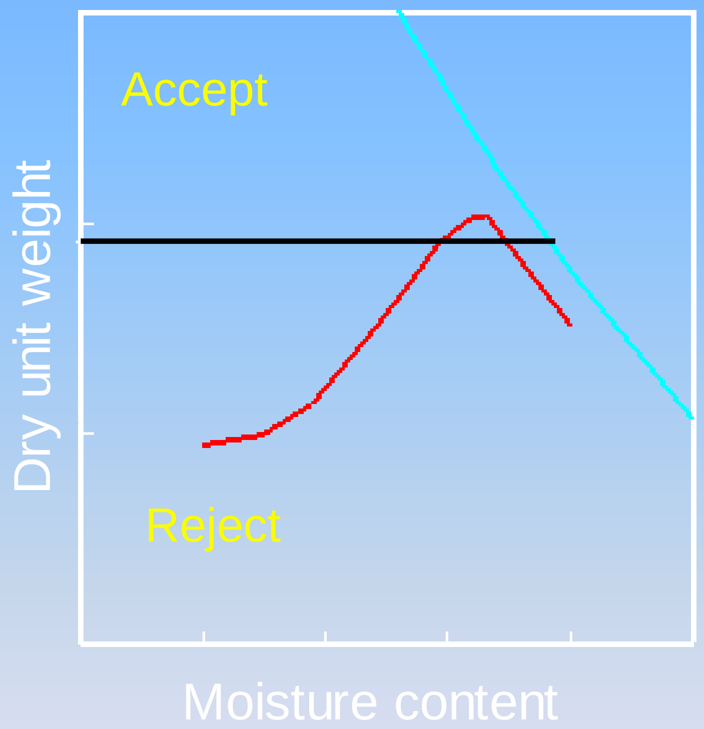
	Typical Values	
	$(\gamma_{dry})_{max}$ (kN/m^3)	m_{opt} (%)
Well graded sand SW	22	7
Sandy clay SC	19	12
Poorly graded sand SP	18	15
Low plasticity clay CL	18	15
Non plastic silt ML	17	17
High plasticity clay CH	15	25

- G_s is constant, therefore increasing maximum dry unit weight is associated with decreasing optimum moisture contents

- Do not use typical values for design as soil is highly

Field specifications

During construction of soil structures (dams, roads) there is usually a requirement to achieve a specified dry unit weight.



(a) > 95% of (modified) maximum dry unit weight

Field specifications

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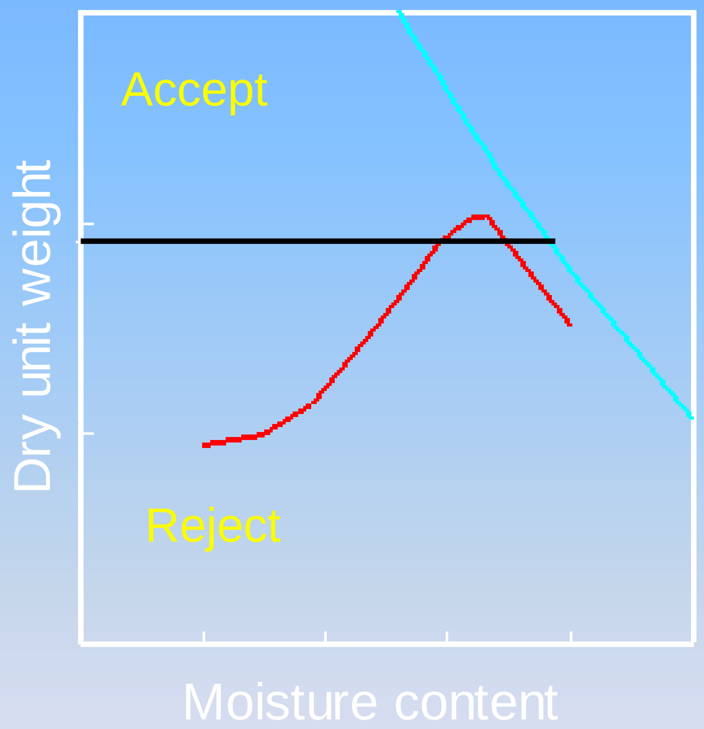

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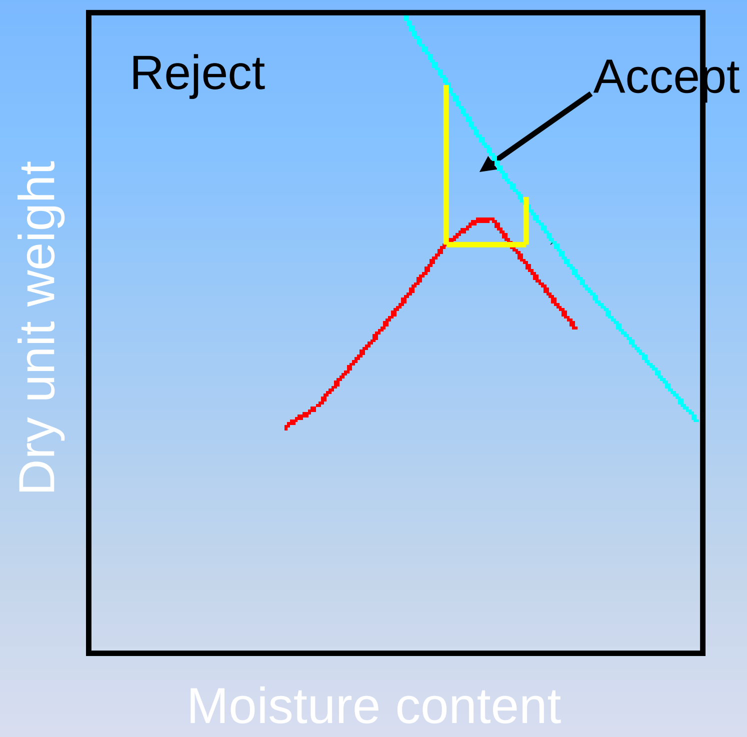

(b) >95% of (modified) maximum dry unit weight and m within 2% of m_{opt}

Compaction equipment

Equipment	**Most suitable soils**
Smooth wheeled rollers, static or vibrating	Well graded sand-gravel, crushed rock, asphalt
Rubber tired rollers	Coarse grained soils with some fines
Grid rollers	Weathered rock, well graded coarse soils
Sheepsfoot rollers, static	Fine grained soils with > 20% fines
Sheepsfoot rollers, vibratory	as above, but also sand-gravel mixes
Vibrating plates	Coarse soils, 4 to 8% fines
Tampers, rammers	All types
Impact rollers	Most saturated and moist soils

Also drop weights, vibratory piles


AND BAR PRODUCTS DIVISION

Sands and Gravels

For (cohesionless)soils without fines alternative specifications are often used. These are based on achieving a certain relative density.

$$I_d = \frac{e_{\max} - e}{e_{\max} - e_{\min}}$$

e = current void ratio

e_{max} = maximum void ratio in a standard test

e_{min} = minimum void ratio in a standard test

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$I_d = 1$ when $e = e_{min}$ and soil is at its densest state

$I_d = 0$ when $e = e_{max}$ and soil is at its loosest state

Sands and Gravels

We can write I_d in terms of γ_{dry} because we have

$$e = \frac{G_s \gamma_w}{\gamma_{dry}} - 1$$

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The terms loose, medium and dense are used, where typically

loose $0 < I_d < 0.333$

medium $0.333 < I_d < 0.667$

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The terms loose, medium and dense are used, where typically

loose $0 < I_d < 0.333$

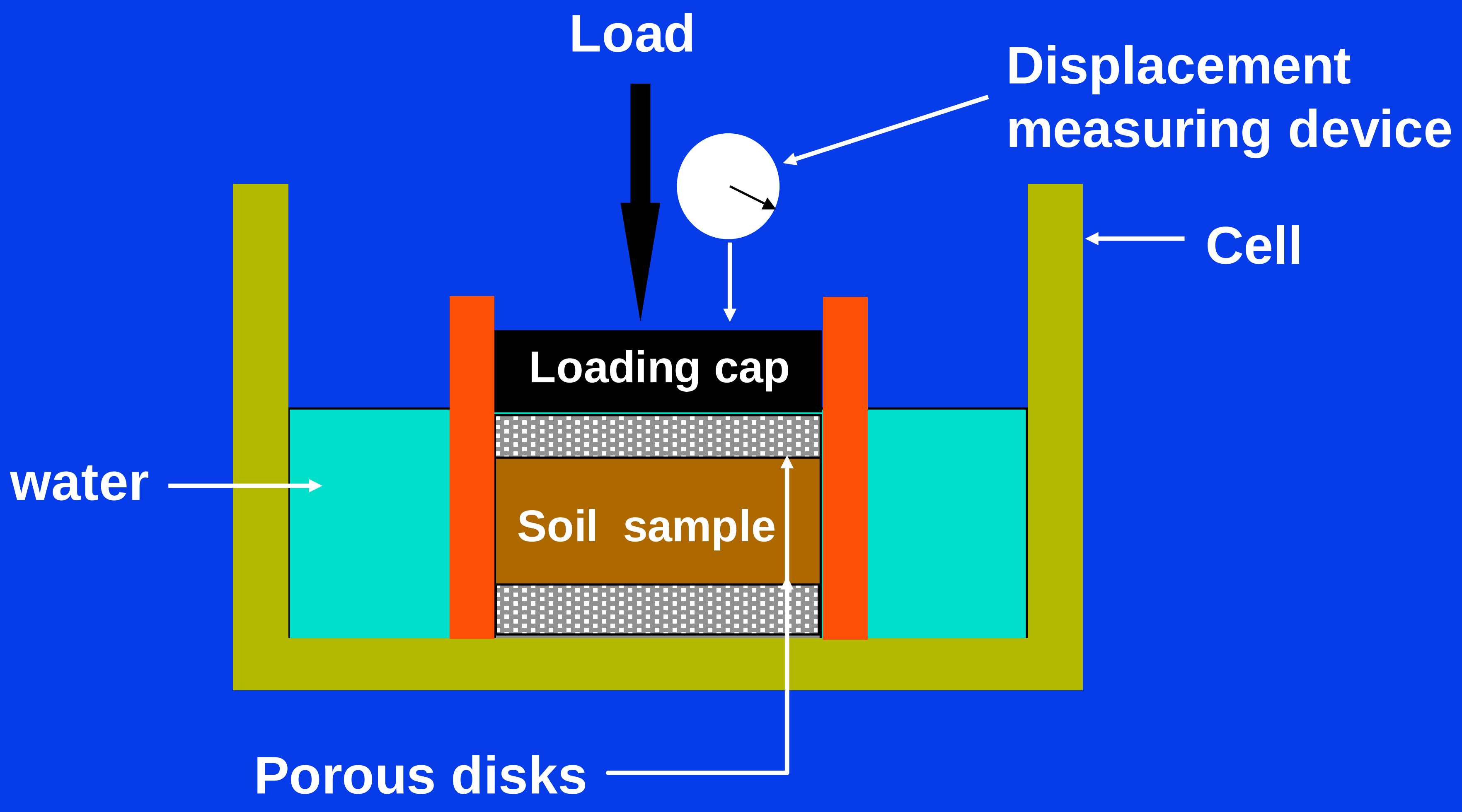
medium $0.333 < I_d < 0.667$

dense $0.667 < I_d < 1$

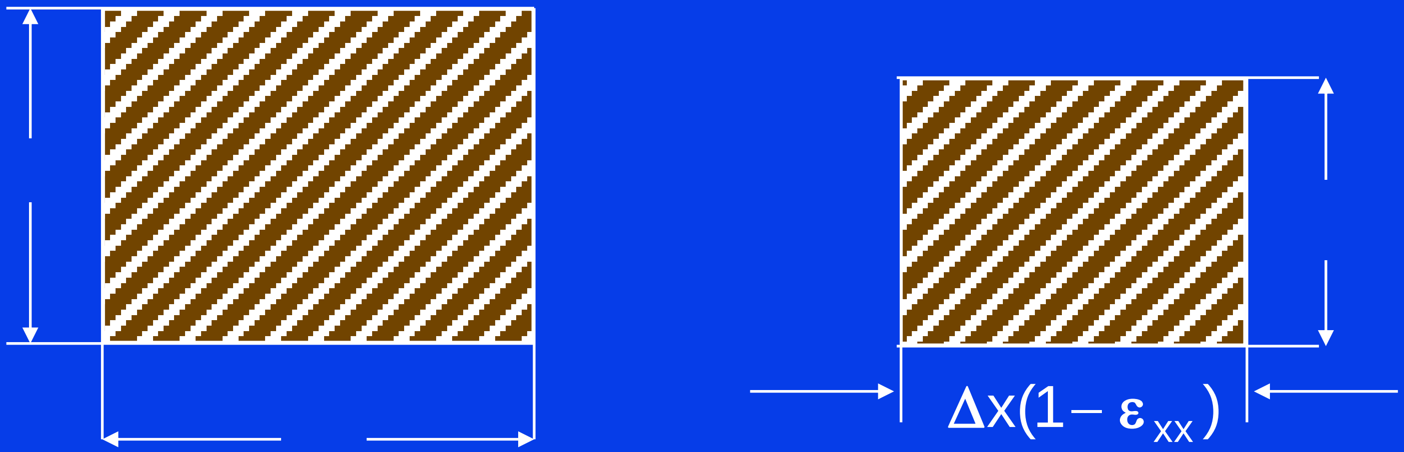
The maximum and minimum dry unit weights vary significantly from soil to soil, and therefore you cannot determine dry unit weight from I_d

Measurement of soil properties

The oedometer apparatus



Relation between axial and volume strain



(a) Before Deformation

(b) After Deformation

Volume strain $$\varepsilon_v = -\frac{\Delta V}{V_0} \qquad (1)$$

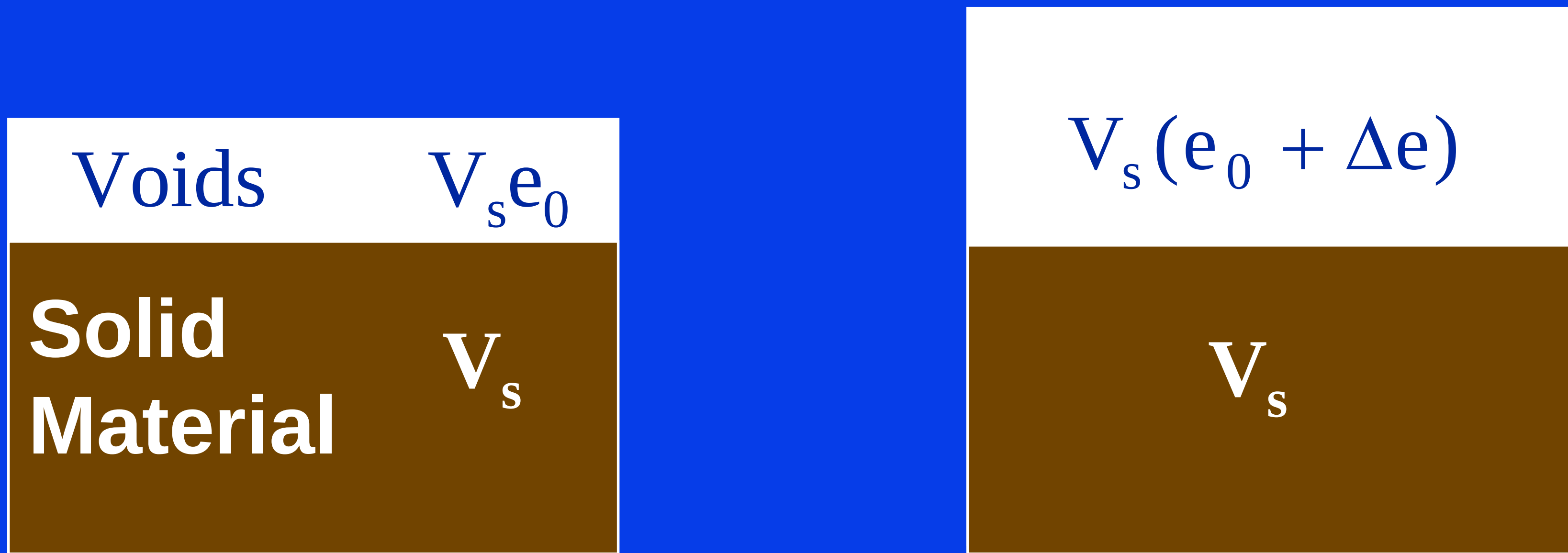
(a) $$V = V_o = \Delta x \, \Delta y \, \Delta z$$

(b) $$V = \left[\Delta x (1 - \varepsilon_{xx})\right] \times \left[\Delta y (1 - \varepsilon_{yy})\right] \times \left[\Delta z (1 - \varepsilon_{zz})\right] \qquad (2a)$$

Relation between axial and volume strain

$$\varepsilon_v = -\left(\frac{V - V_0}{V_0}\right) \qquad (2b)$$

Relation between volume strain and voids ratio



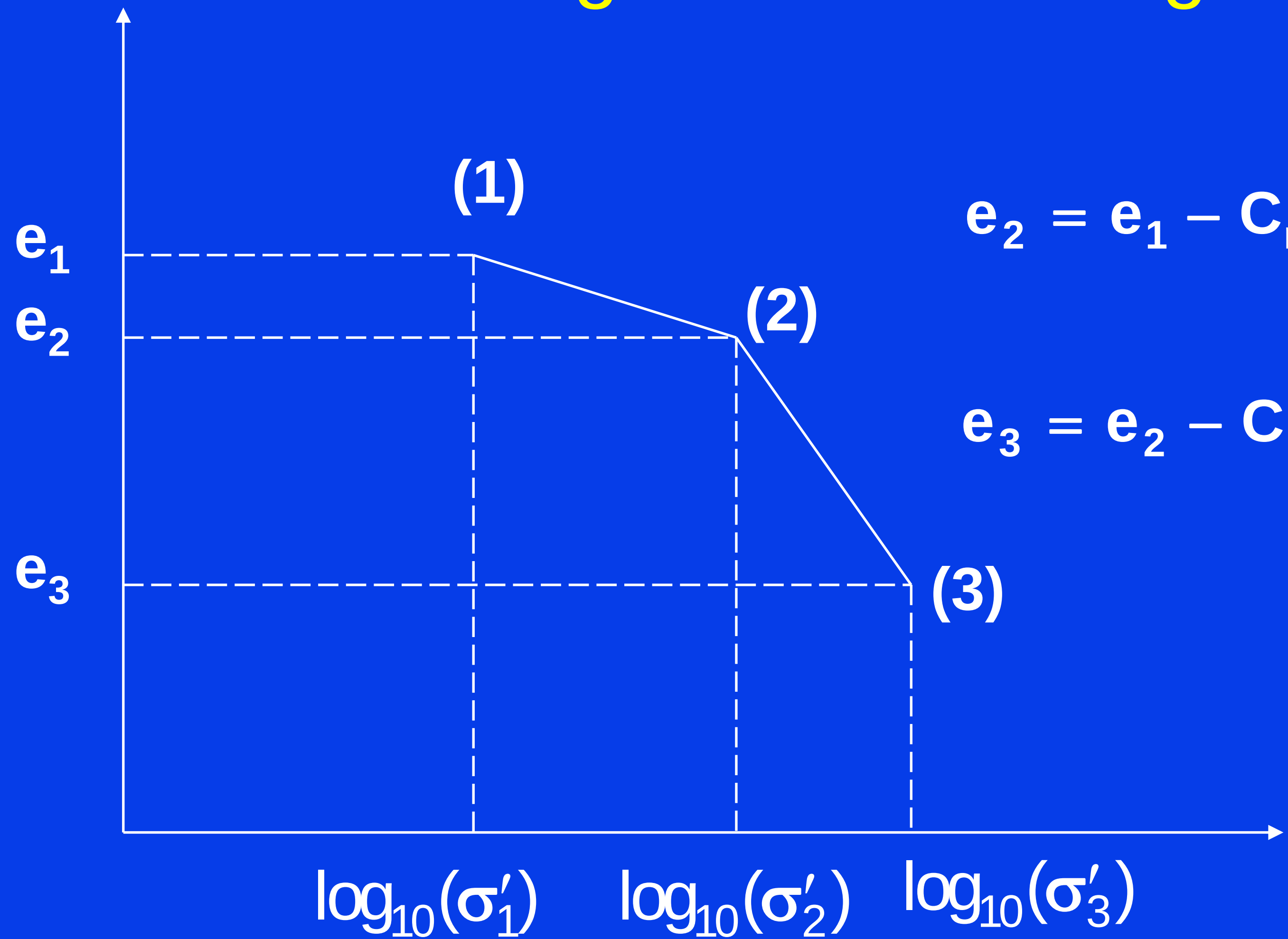
(a) Before Deformation

(b) After Deformation

$$V_0 = V_s(1 + e_0)$$

$$V = V_s(1 + e_0 + \Delta e)$$

Voids ratio change for soil moving from OC to NC



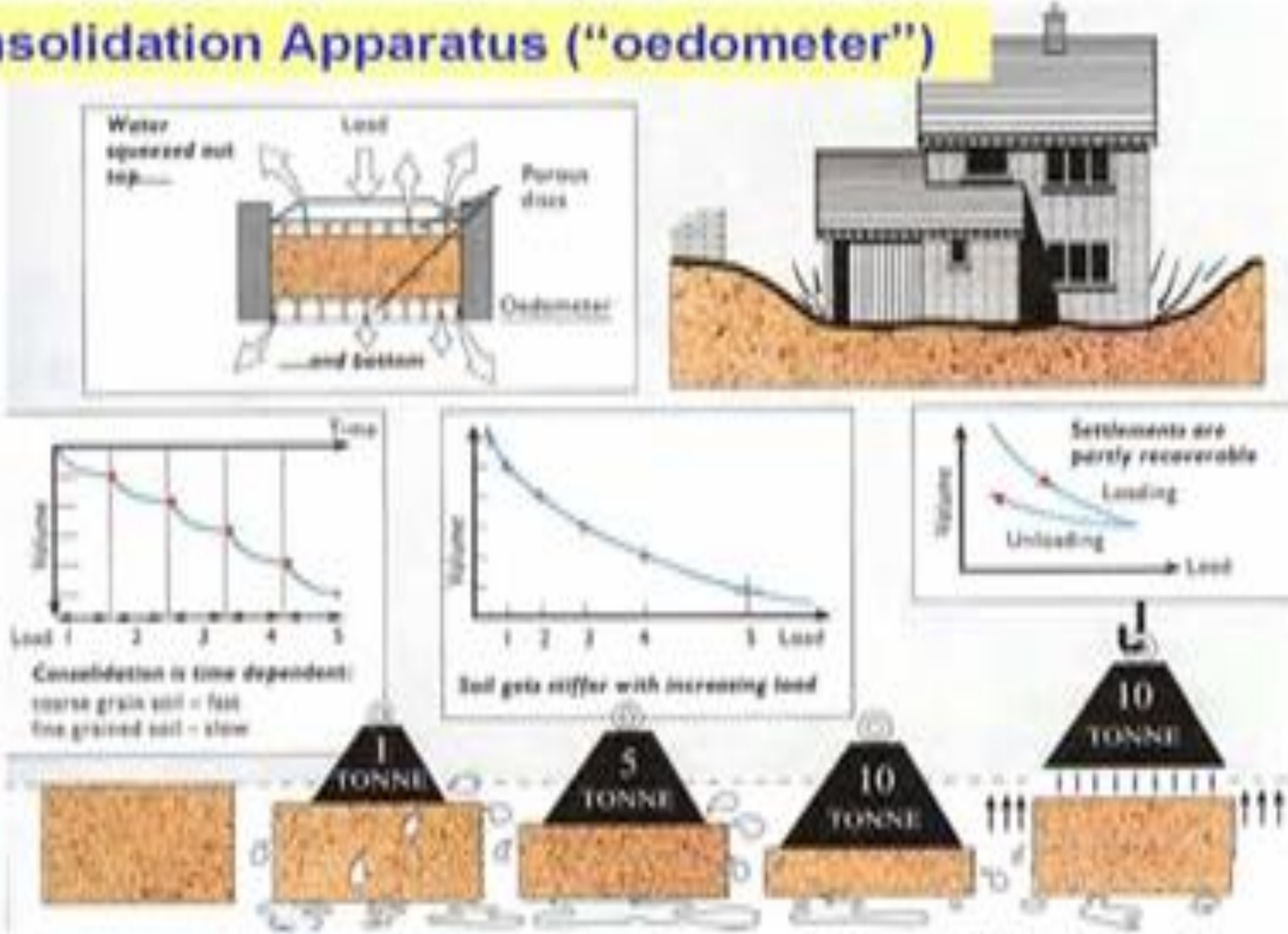
$$e_2 = e_1 - C_r \log_{10}\left(\frac{\sigma'_2}{\sigma'_1}\right) \quad (8a)$$

$$e_3 = e_2 - C_c \log_{10}\left(\frac{\sigma'_3}{\sigma'_2}\right) \quad (8b)$$

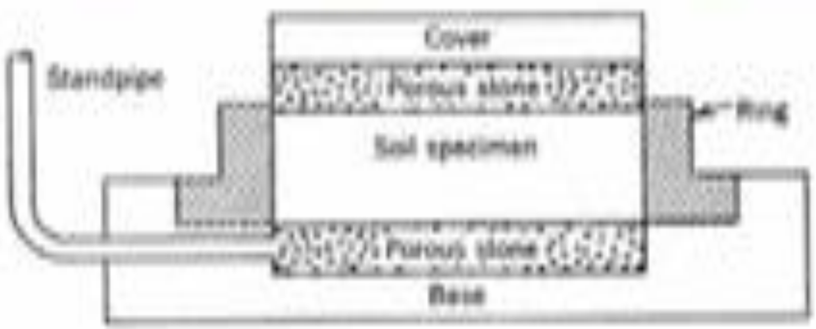
The initial value of $\sigma'_{pc} = \sigma'_2$

The final value of $\sigma'_{pc} = \sigma'_3$

Consolidation Apparatus ("oedometer")



ELE catalogue


Cover
Standpipe
Porous stone
Ring
Soil specimen
Porous stone
Base

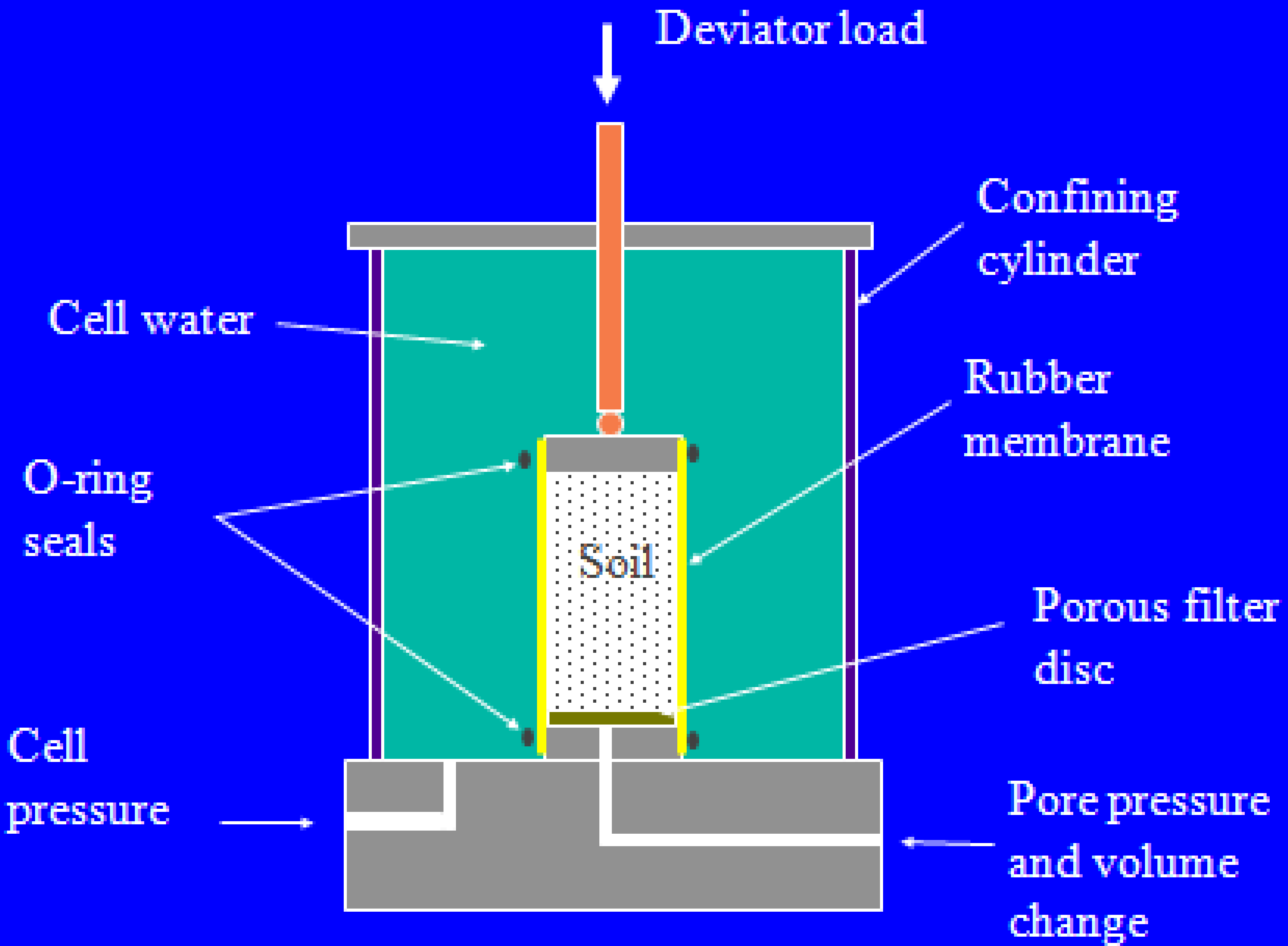
Oedometers

Unconfined compression test on clay (undrained, uniaxial)

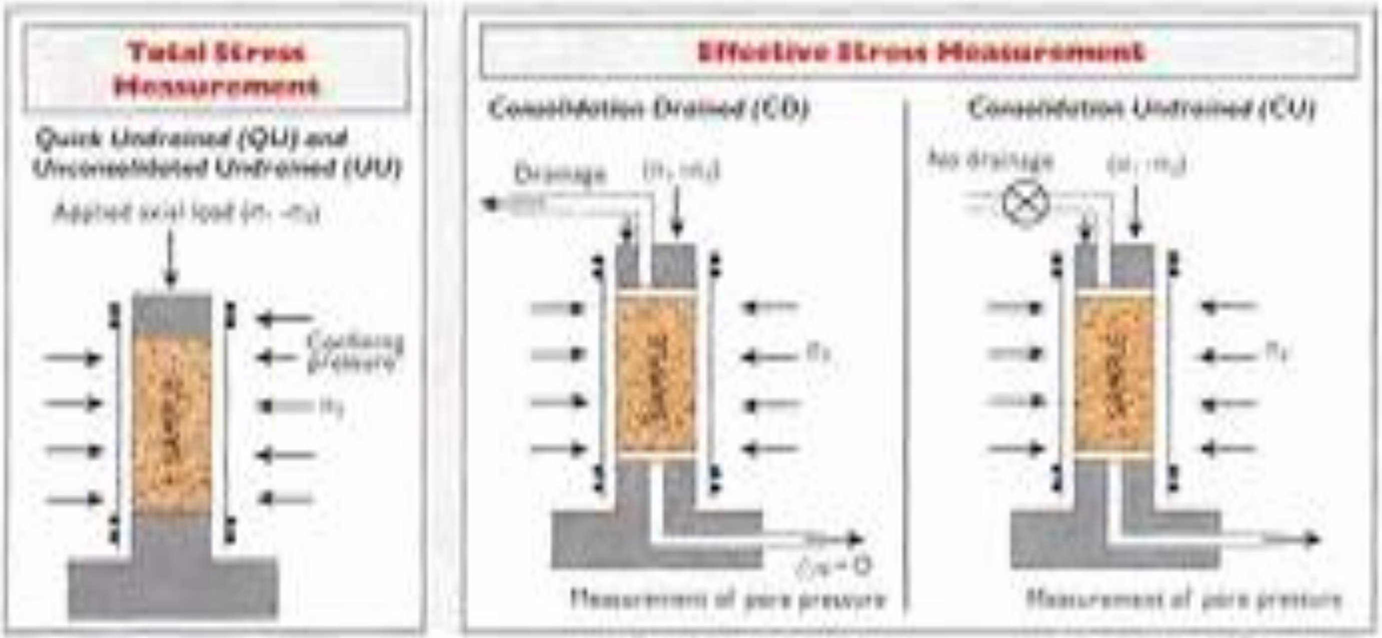
ELE catalogue

Tests to measure soil strength

2. The Triaxial Test

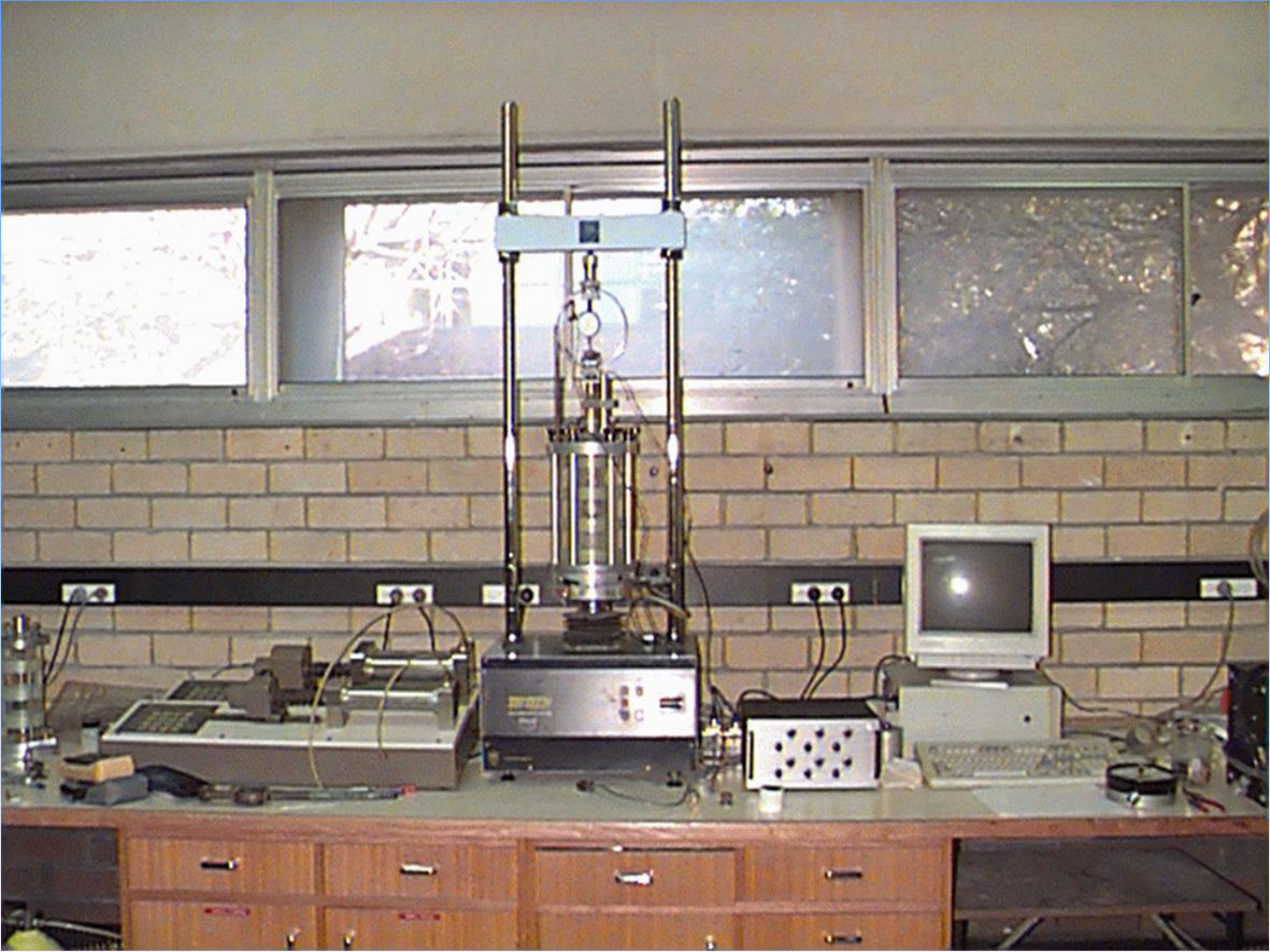


Triaxial Test on Soil Sample in Laboratory



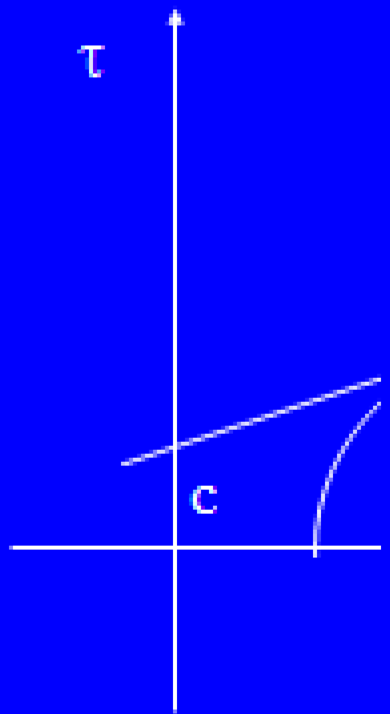
Triaxial test on soil

ELE catalogue

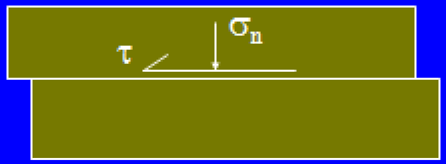


Mohr Circles

To relate strengths from different tests we need to use some results from the Mohr circle transformation of stress.



Mohr-Coulomb failure criterion



$+ \quad \sigma \tan \phi$

The limiting shear stress (soil strength) is given by

$$\tau = c + \sigma_n \tan \phi$$

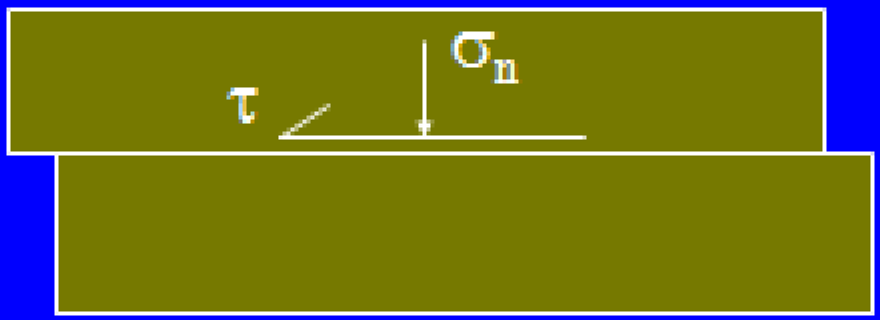
where c = cohesion (apparent)

ϕ = friction angle

σ

The Mohr-Coulomb failure locus is tangent to the Mohr circles at failure

Mohr-Coulomb failure criterion



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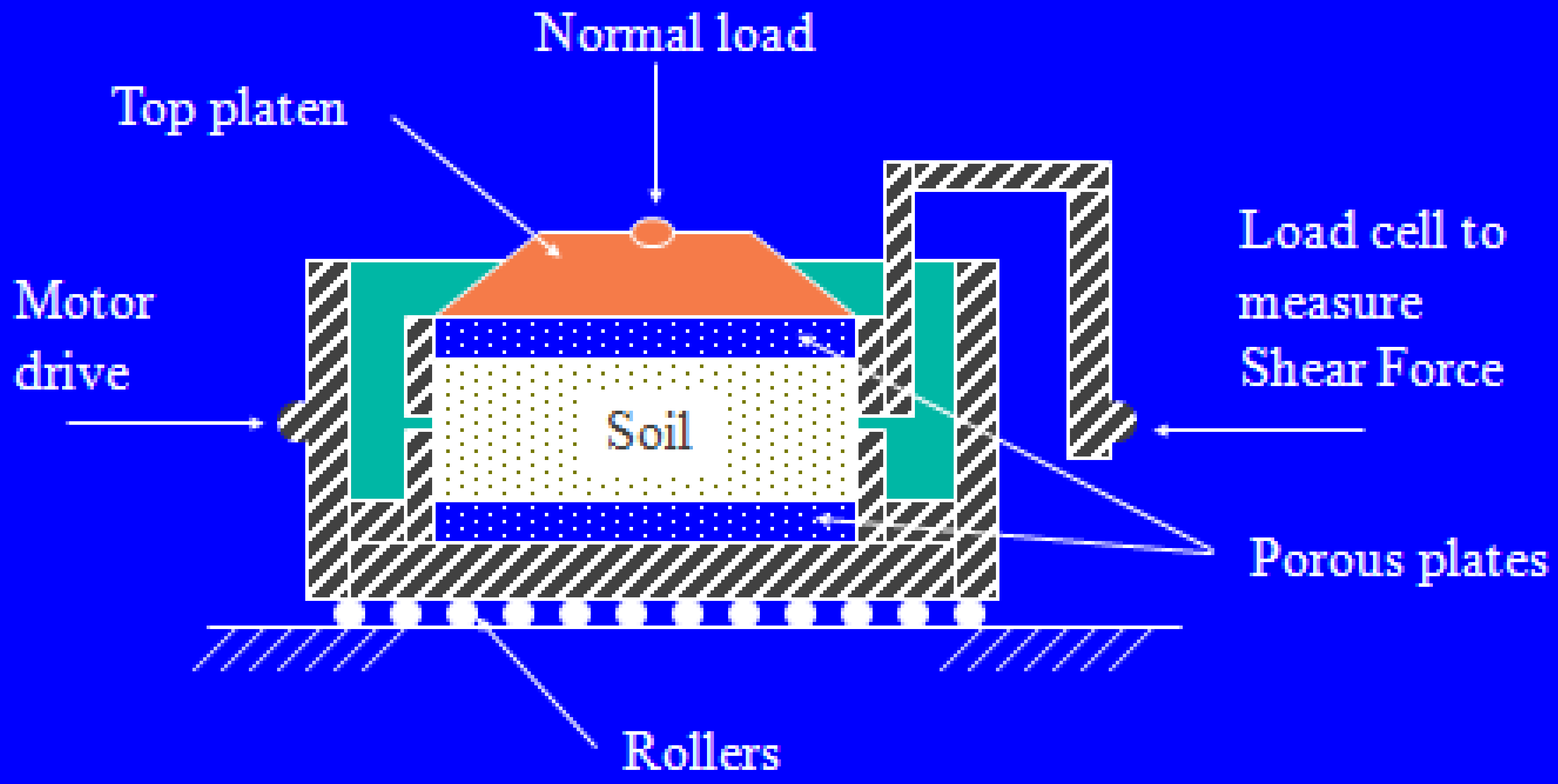
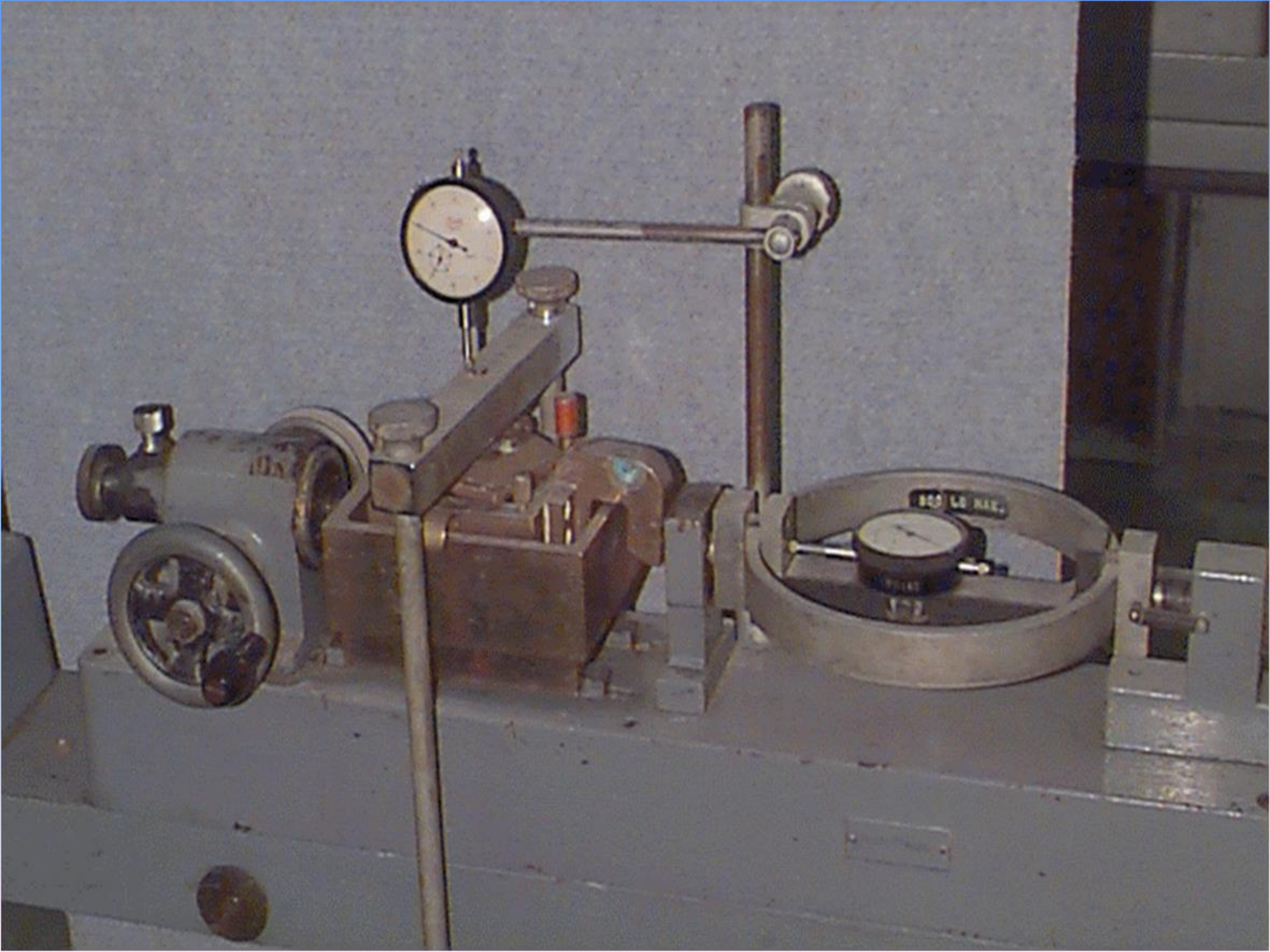
Tests to measure soil strength

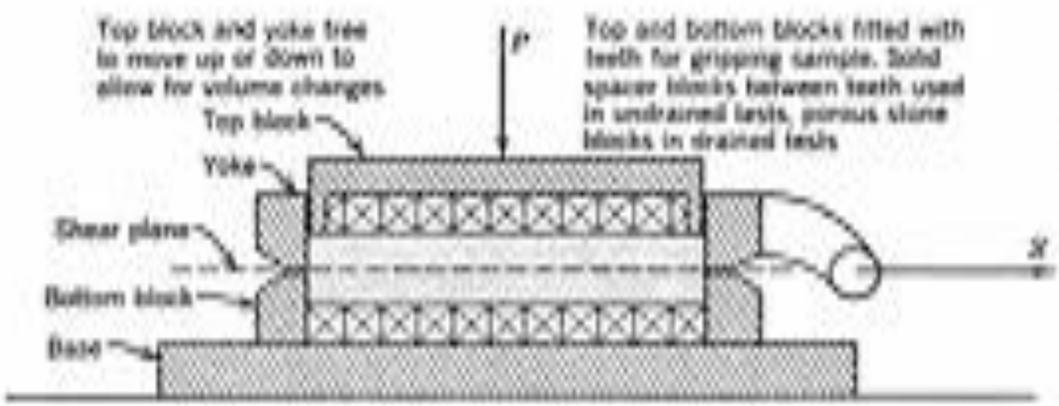
1. Shear Box Test



Measure relative horizontal displacement, dx

vertical displacement of top platen, dy





Direct shear (shear box) test on soil

ELE catalogue

Shear box test

- Usually only relatively slow drained tests are performed in shear box apparatus. For clays rate of shearing must be chosen to prevent excess pore pressures building up. For sands and gravels tests can be performed quickly
- Tests on sands and gravels are usually performed dry. Water does not significantly affect the (drained) strength.
- If there are no excess pore pressures and as the pore pressure is approximately zero the total and effective stresses will be identical.
- The failure stresses thus define an effective stress failure envelope from which the effective (drained) strength parameters c', ϕ' can be determined.