DETERMINATION OF CONSOLIDATION PARAMETERS

DR. IR. NURLY GOFAR, MSCE

CONSOLIDATION TEST

- Dari pembahasan sebelum ini, komponen terbesar dari penurunan pondasi / tanah (terutama untuk tanah lempung) adalah yang diakibatkan oleh proses konsolidasi. Oleh karena itu perlu dijelaskan dasar dasar penentuan parameter konsolidasi
- Ada tiga jenis pengujian konsolidasi yaitu : (1) Standar Oedometer Test; (2) Large strain consolidation test (Rowe Cell); (3) Constant Rate of Strain Test (CRS)

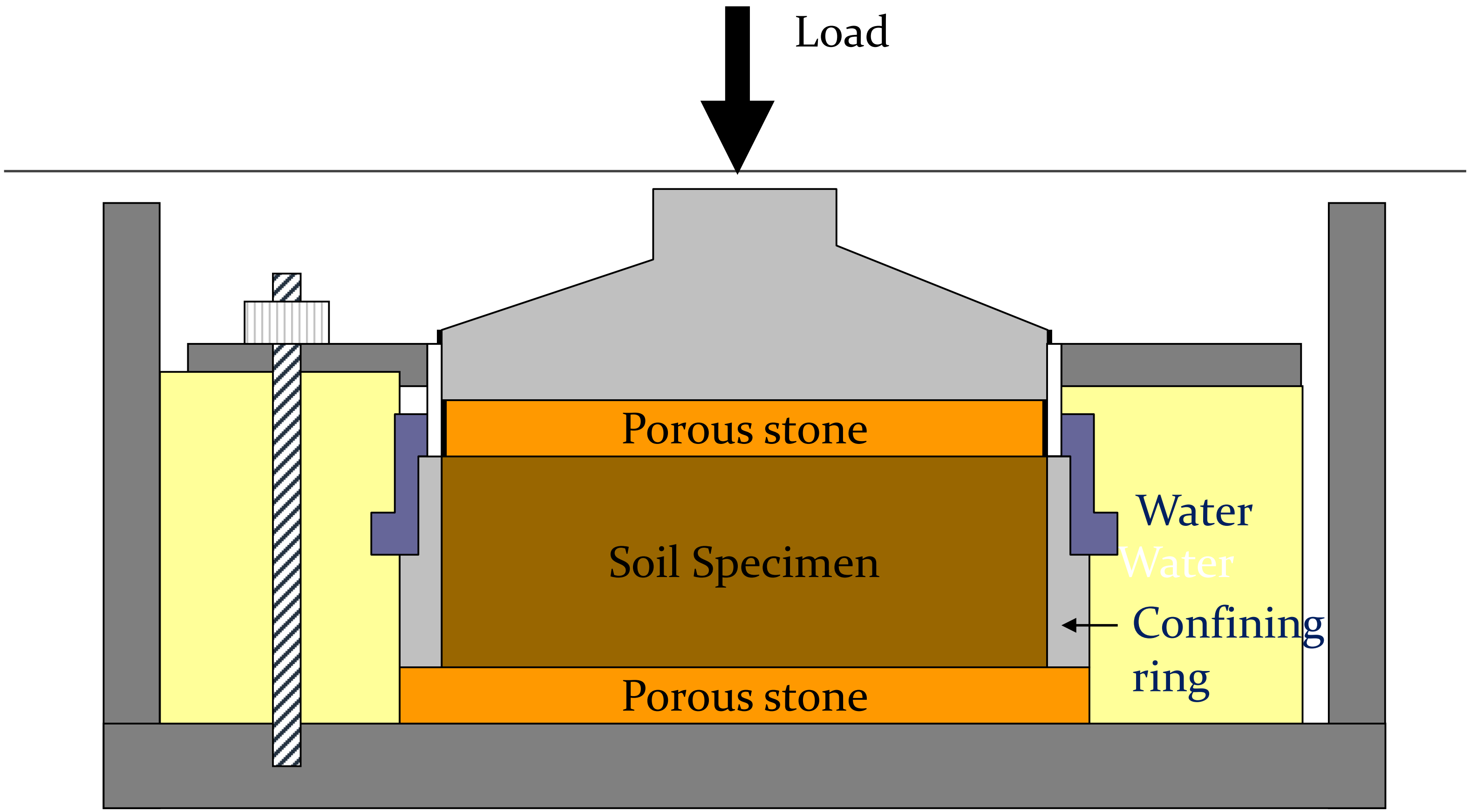
Ref: Bardett, JP (1997). Experimental Soil Mechanics, Prentice Hall. Chapter 6.

History of Consolidation Test

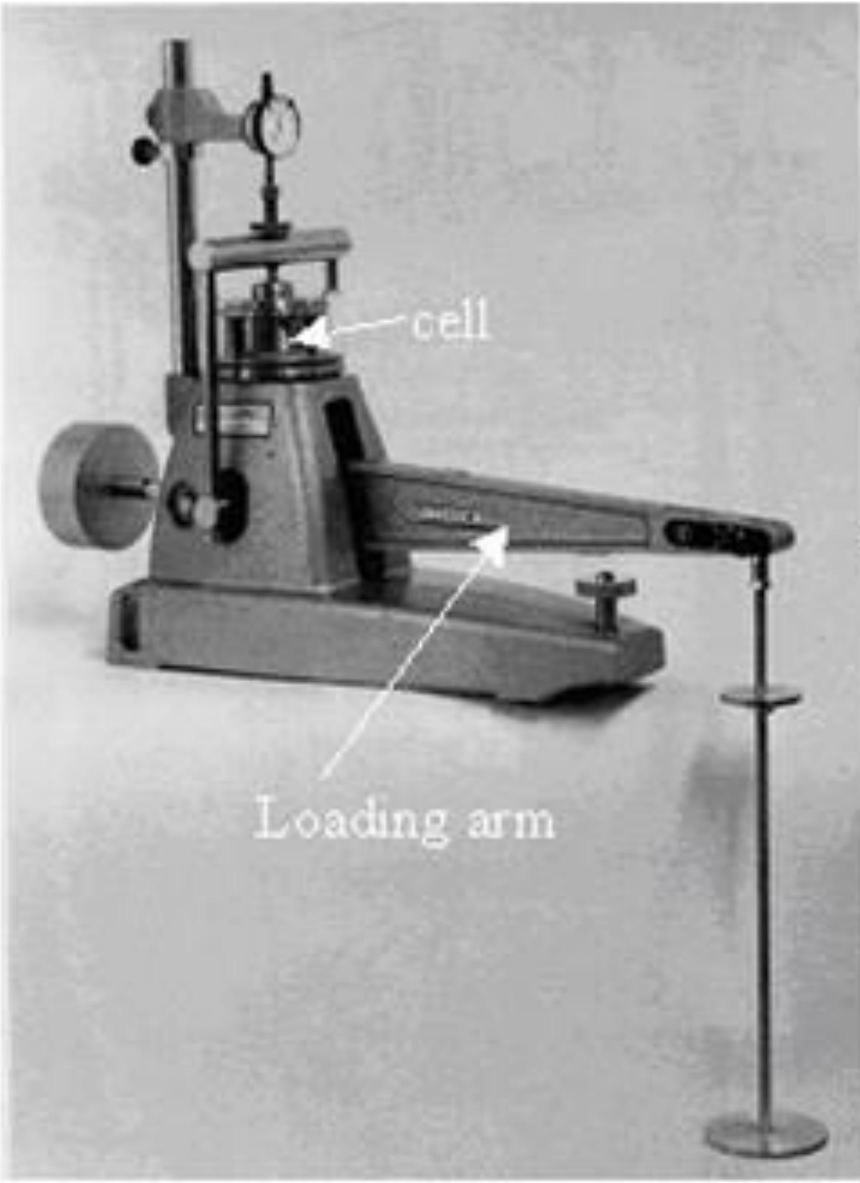
- 1809 Thomas Telform was the first to use the term “consolidation”
- 1901 Consolidation test was invented
- 1910 D. E. Morgan invented the floating ring
- 1923 Karl Terzaghi worked on consolidation theory

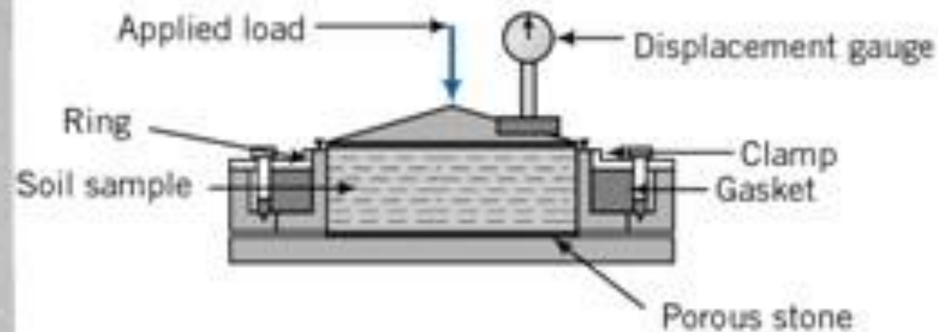
Currently, **Oedometer** test is still considered as the standard consolidation test in many countries

Standard Oedometer Test

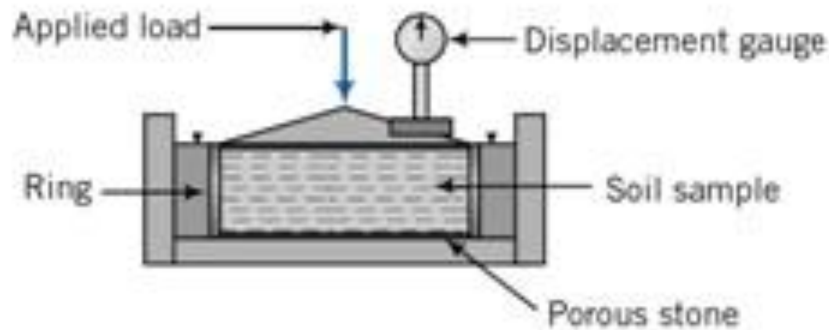


Ref: [sni-2812--2011]





(*b*) Fixed ring cell



(*c*) Floating ring cell

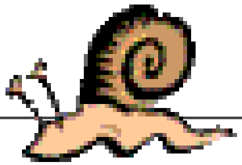
Procedure

- The test procedure has been standardized in BS 1377 (Part 5), ASTM D 2435-2011 and SNI 2812-2011
- The soil specimen, in the form of a disc with a certain diameter and thickness, is placed in between two porous stones and held inside a metal ring. The ring imposes a condition of no lateral strain on the specimen and the porous stones allow a 1-dimensional flow of water from the soil specimen. The specimen is trimmed to fit the consolidation ring and placed on top of the bottom porous stone.
- Once set, the specimen will be loaded in a series of pressure; each being doubled the previous value (LIR = 1). The initial weight depends on the soil type and the depth where the soil is taken from the field. Each pressure is normally maintained for 24 hours. During this time, deformation of specimen will be observed in specified time (e.g. ¼, ½, 1, 2, 4, 9, 15, 30, 60, 120, 1440 minutes).

Assumptions

- Saturated clay layer
- Laterally confined
- One dimensional flow
- Constant permeability
- Can be measured by oedometer Test

Problems related to conventional consolidation tests:

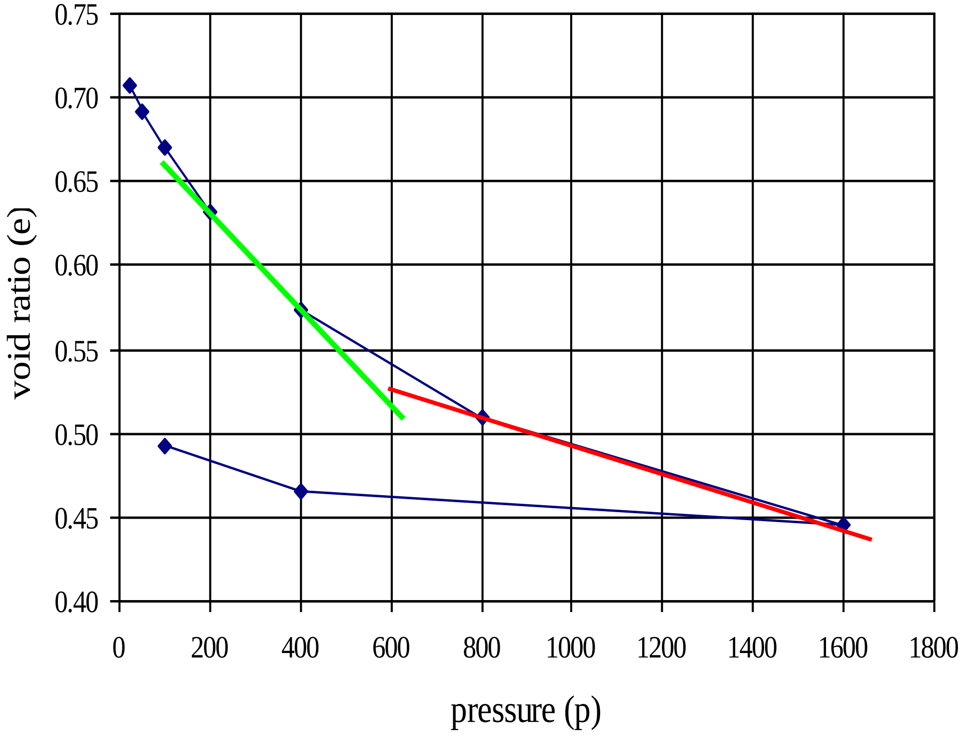


1. **Length of time** required for completion (about 8 days for standard test or months for test on soft organic or peat soil)
2. Sudden shock at initial reading
3. Load increment ratio (LIR) usually = 1 ; but use lower LIR for soft-sensitive soil
4. Load Increment duration (LID) 24 hr for inorganic soil; 1 week for organic soil. pwp measurement is required for research purpose.
5. Standard size of oedometer sample, diameter 52 mm and thickness 200 mm
6. Keep soil saturated by keeping the water level above soil sample. Need to backpressure for research purpose
7. Boundary impedance. Keep the quality of porous stone by boiling each time it is used.
8. Ring friction: Use grease OR use consolidation ring made of cadmium →lowest friction coefficient →less error
9. Temperature: Keep room temperature constant at 20^{o}C

Data Analysis – Stress Strain curve

Results of consolidation testing are presented by plotting:

✓ *the void ratio (e) at the end of each increment period against the corresponding effective stress (linear scale)* ***or e-p' curve***



$$a_v = \frac{\Delta e}{\Delta \sigma} = \frac{e_1 - e_2}{\sigma'_1 - \sigma'_2}$$

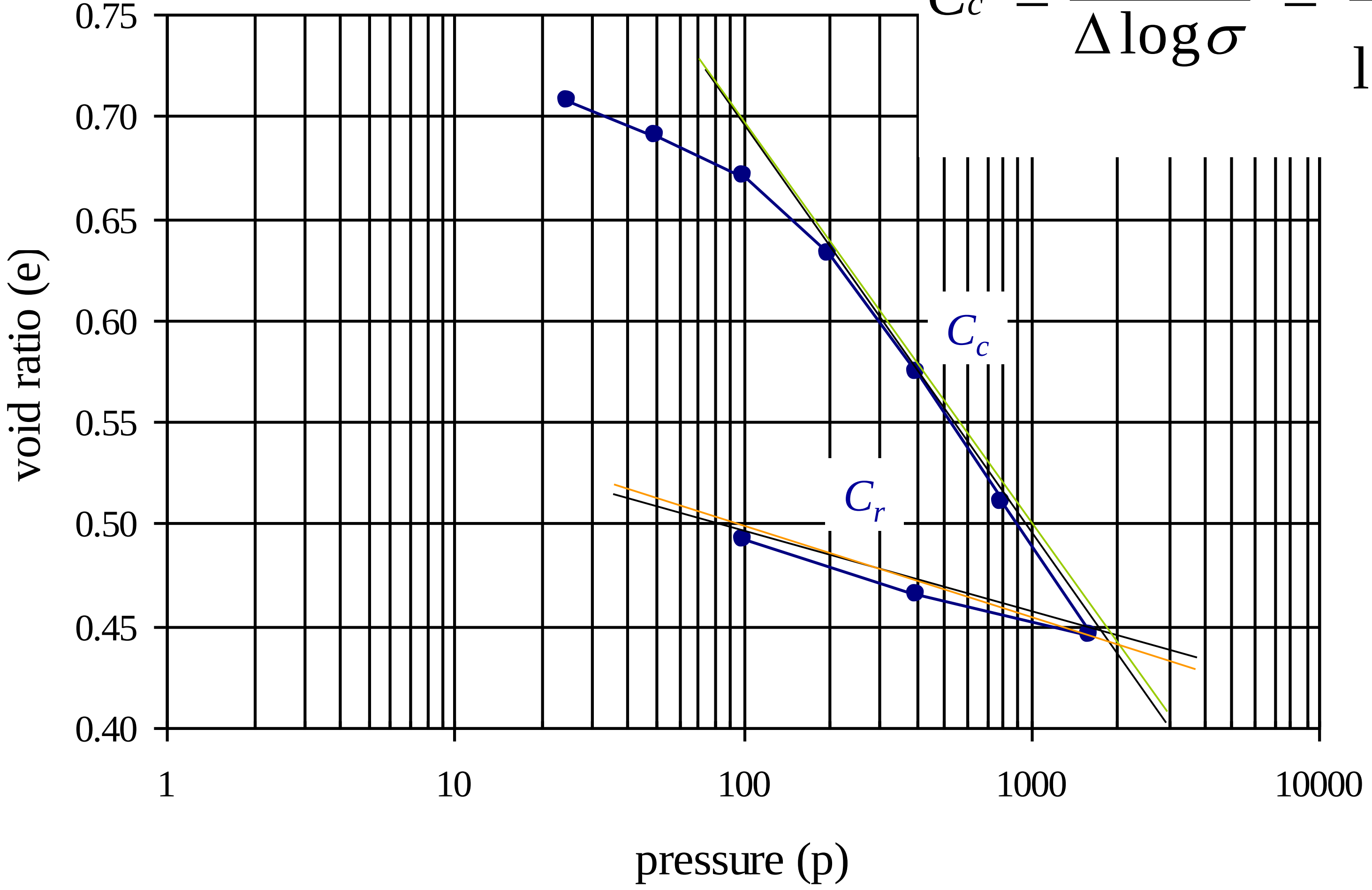
$$m_v = \frac{a_v}{1+e_o} = \frac{1}{1+e_o}\left(\frac{e_o - e_1}{\sigma'_1 - \sigma'_2}\right)$$

Problems:

The value of m_v is not constant, and only true for a certain range of stress.

✓ ***the void ratio (e) at the end of each increment period against the corresponding effective stress (log scale) or e-log p' curve***

$$C_c = \frac{\Delta e}{\Delta \log \sigma} = \frac{e_1 - e_2}{\log \frac{\sigma_2}{\sigma_1}}$$



Empirical formula & Correlation with other properties

Empirical Formulas, correlation of Cc with liquid limit, void ratio, and water content

Empirical formula	Soil type
$C_c = 0.009\,(LL - 10)$	All clay (undisturbed)
$C_c = 0.007\,(LL - 10)$	Remolded soil
$C_c = 1.15\,(e_o - 0.35)$	All clay (undisturbed)
$C_c = 0.30\,(e_o - 0.27)$	An organic soil
$C_c = 1.15 \times 10^{-2}\,\omega_n$	Organic soil
$C_c = 0.75\,(eo - 0.50)$	Low plasticity soil

Based on Critical State model (Wroth & Wood (1978)

$$C_c = G_s \frac{PI}{200}$$

Correlation between C_c and C_r

- ✓ Recompression index (C_r) can be estimated as *0.05 – 0.20 Cc*
- ✓ C_r generally between *0.015 – 0.035* (Leonards, 1976)
- ✓ Critical State concept

$$C_r = C_c\,(1\text{-}A)$$

for $G_s = 2.7$, and $A = 0.8$ → $C_r = PI/370$

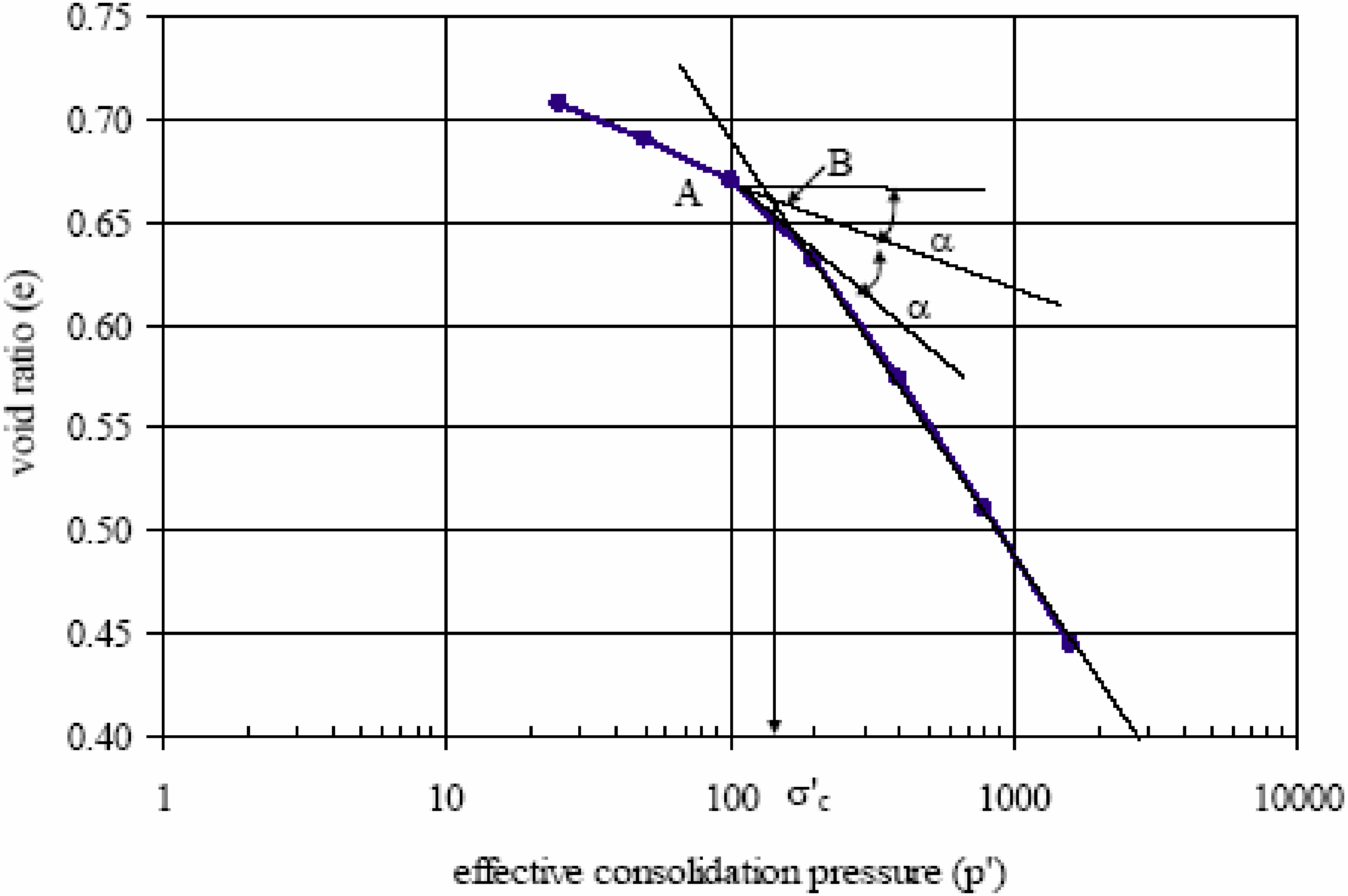
Overconsolidated Soil

Over-consolidated soil is the soil that has undergone recompression in oedometer test.

Over-consolidation is judged if pre consolidation pressure σ'_c obtained from e-log p' curve based on oedometer test is greater than the currently existing overburden pressure (σ'_o). OR C_c obtained from test < C_c = 0.009 (LL-10) OR LI is between 0 to 0.6

$$OCR = \frac{\sigma'_c}{\sigma'_o}$$

The pre-consolidation pressure σ'_c should be estimated based on e-log p curve


0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
void ratio (e)
A
B
α
α
1
10
100
σ'c
1000
10000
effective consolidation pressure (p')

1. Choose by eye the point of maximum curvature on the consolidation curve (point A)
2. Draw a horizontal line from point A
3. Draw a line tangent to the curve at point A
4. Bisect the angle made by step 2 and 3
5. Extent the straight line portion of the virgin compression curve up to where it meets the bisector line obtained in step 4. The point of intersection of these two lines is the approximate value of the pre-consolidation pressure (point B)

Mechanism causing pre-consolidation

- ✓ Changes in total stress due to:
  - Excavation
  - Structure
- ✓ Changes in pore water pressure due to:
  - rise of ground water elevation
  - artesian pressure
  - Pumping or dewatering
- ✓ Changes in soil structure due to secondary pressure
- ✓ Environmental changes: pH, temperature, salt content
- ✓ Climate, precipitation, cementation,
- ✓ Creep

Insitu *e* - log *p'* curve

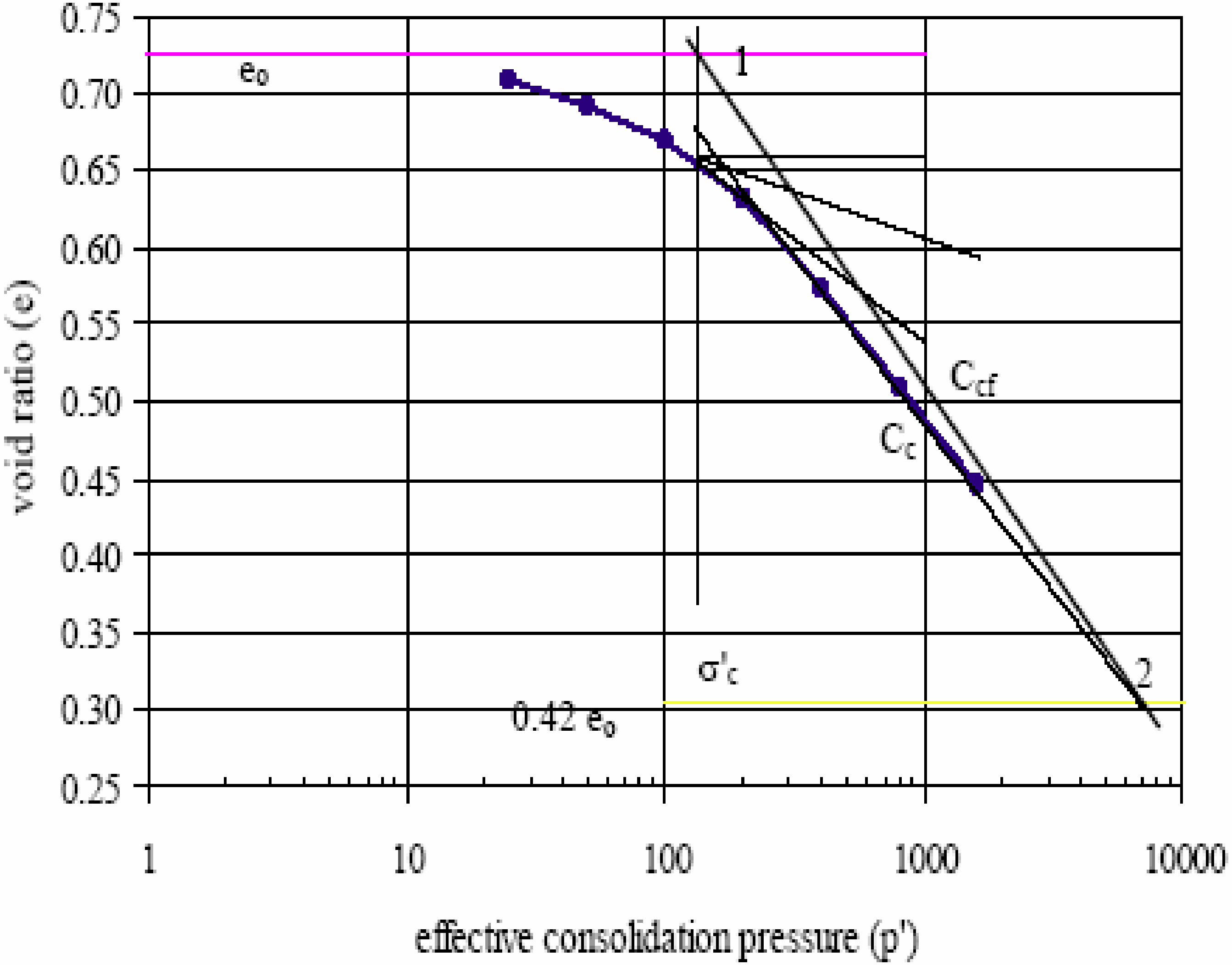
Due to effect of sampling and preparation, the specimen in the Oedometer test will be slightly disturbed

→ decrease in the slope of the compression line

C_c actual > C_c measured

The field virgin compression line should be estimated based on the e-log p curve

Obtaining the field consolidation line



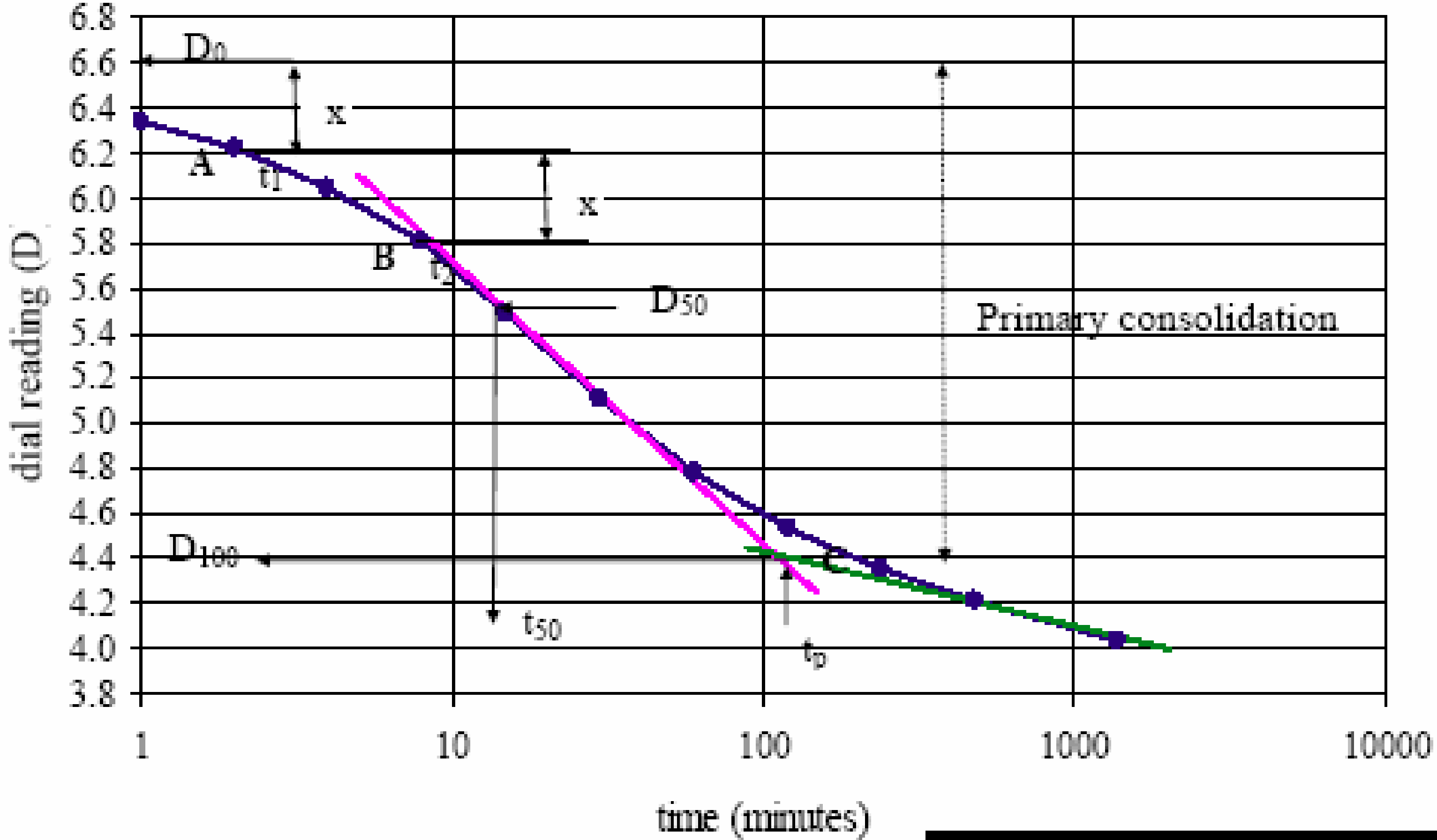
1. Produce two horizontal lines at e_o and 0.42 e_o
2. Produce a vertical line at pressure equal to σ'_o or σ'_c. This line should intersect the horizontal line at e_o at point 1.
3. Plot compression line (C_c) based on the oedometer test. The line will intersect the horizontal line at 0.42 e_o at point 2.
4. Draw a line from point 1 to point 2. The slope of this line is the field compression index (C_{cf}).

DATA ANALYSIS
Settlement-Time Relationship
Determination of C_v

Log time method – Cassagrande

Square root time method- Taylor

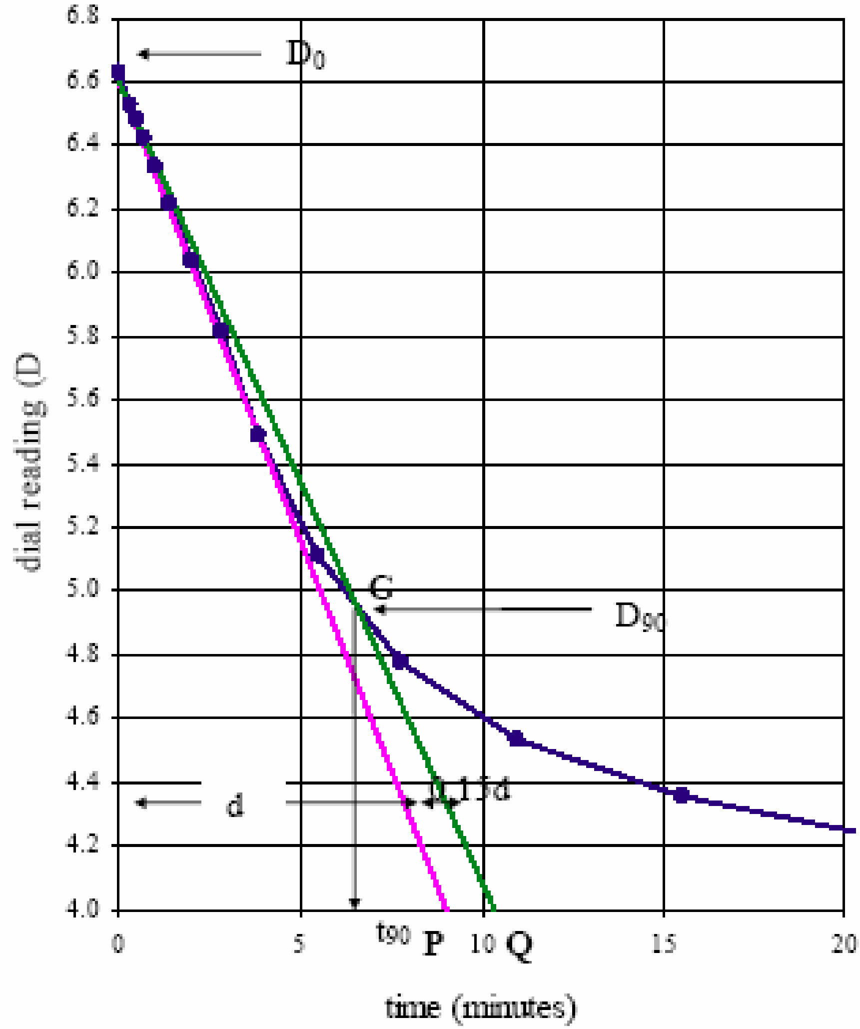
Log time method (Cassagrande)



Most of the time it is difficult to get this straight line

1. Plot a graph relating dial reading (mm) versus log time
2. Produce a straight line for primary consolidation and secondary consolidation part of the graph. The two lines will meet at point C.
3. The ordinate of point C is D_{100} = the deformation corresponds to U = 100%
4. Select time t_1 (point A), $t_2 = 4t_1$ (point B), $t_3 = 4t_2$ etc. The difference in the dial reading is equal to x.
5. An equal distance x set off above point A fixes the point D_o = the deformation corresponds to U =0%. Notes that D_o is not essentially equal to the initial reading may be due to small compression of air within the sample.
6. The compression between D_o and D_{100} is called the primary consolidation.
7. A point corresponding to U = 50% can be located midway between D_o and D_{100}. The value of T corresponds to U = 50% is 0.196.
8. Thus $$C_v = \frac{0.196 H_d^2}{t_{50}}$$ where H_d = half the thickness of the specimen

Square root of time method (Taylor)



1. Extent the straight line part of the curve to intersect the ordinate (t = 0) at point D. The point shows the initial reading (D_o). The intersection of this line with the abscissa is P.

2. Take point Q such that OQ = 1.15 OP.

3. The intersection of line DQ and the curve is called point G

4. Draw horizontal line from G to the ordinate (D_{90}). The point shows the value of $\sqrt{t_{90}}$. The value of T corresponds to U = 90% is 0.848.

5. Thus

$$C_v = \frac{0.848\, H_d^{\;2}}{t_{90}}$$

H_d is half the thickness of specimen for a particular pressure increment.

How do we get the factor 1.15

$$d_{90} = F\sqrt{0.848}$$

$$\tfrac{9}{5}\, d_{50} = \tfrac{9}{5}\, F\sqrt{0.197}$$

$$\frac{d_{90}}{\tfrac{9}{5}\, d_{50}} = \frac{F\sqrt{0.848}}{\tfrac{9}{5}\, F\sqrt{0.197}} = 1.1525 \approx 1.15$$

SQUARE-ROOT OF TIME VS LOG TIME METHOD

- Generally square root of time method is better
- Square root of time methods usually gives lower C_v
- Square root of time method is easier to program in computer
- k computed from C_v almost always less then measured value; slower compression
- To decide which is correct → compare the k value

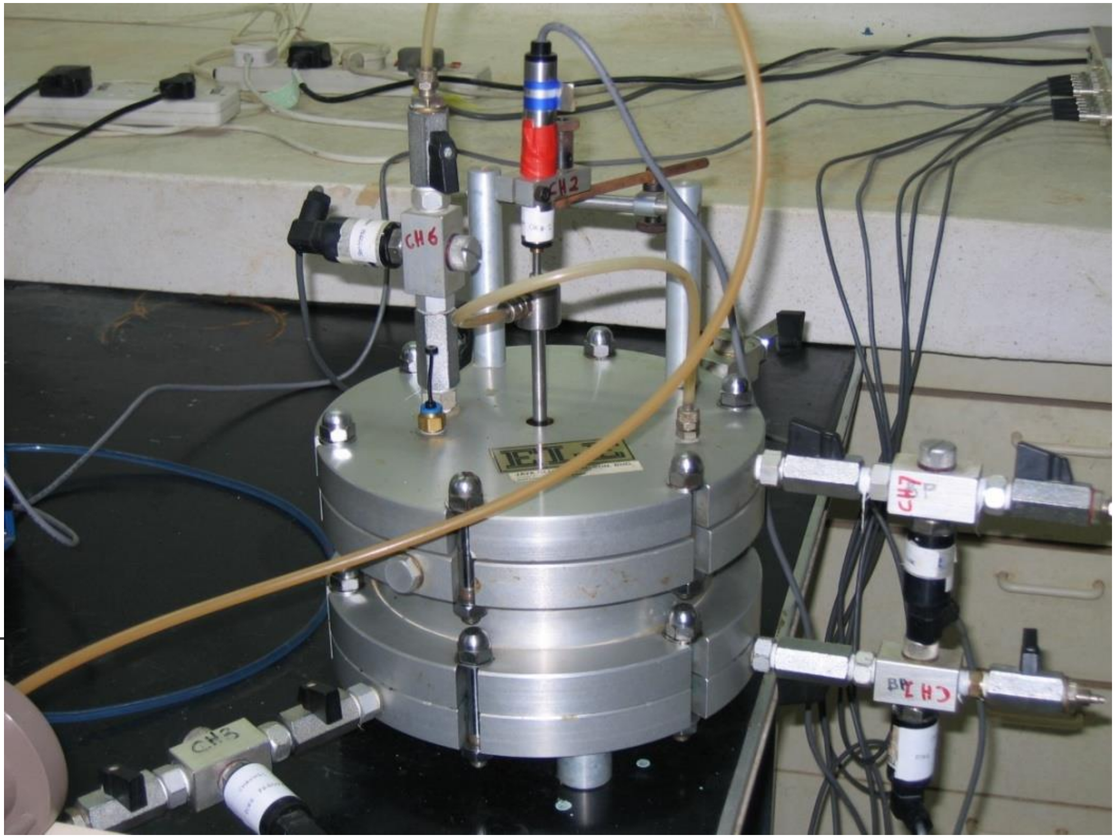
SQUARE-ROOT OF TIME VS LOG TIME METHOD

- The square root of time method works well based on the assumption of NO secondary consolidation.
  - The method is OK because Terzaghi theory does not account for secondary compression anyway

- Use strictly for vertical drainage only
- Cannot be used for some soils such as peat for which *k* changes very much when subjects to the change in effective stress.

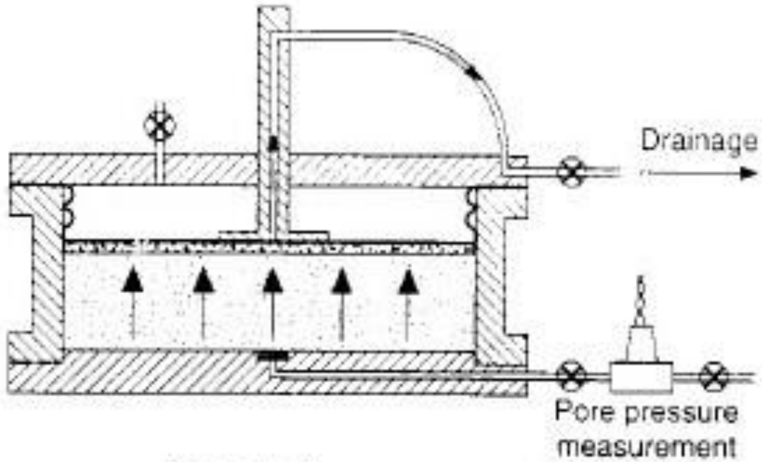
Other consolidation tests

Large strain consolidation test Rowe Cell

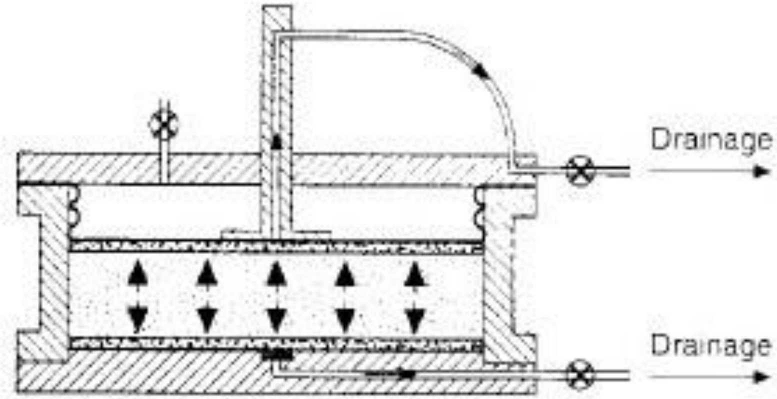


Introduced by Rowe & Barden (1966)
Standard ASTM D2435-90, Head (1986)

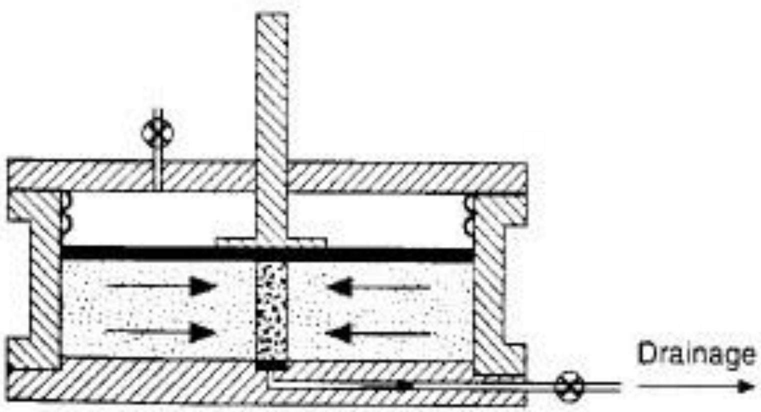
Types of test in Rowe Cell



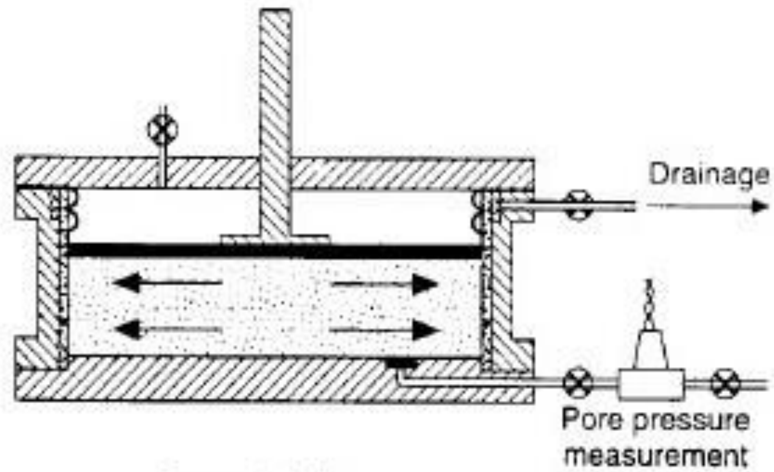
Single drainage (vertical flow)



Double drainage (vertical flow)



Inward drainage (horizontal flow)



Outward drainage (horizontal flow)

Constant Rate of Strain (CRS) Test

Standard ASTM D4186-89,
Head (1986), Lowe et. al. (1969)

Experimental Setup

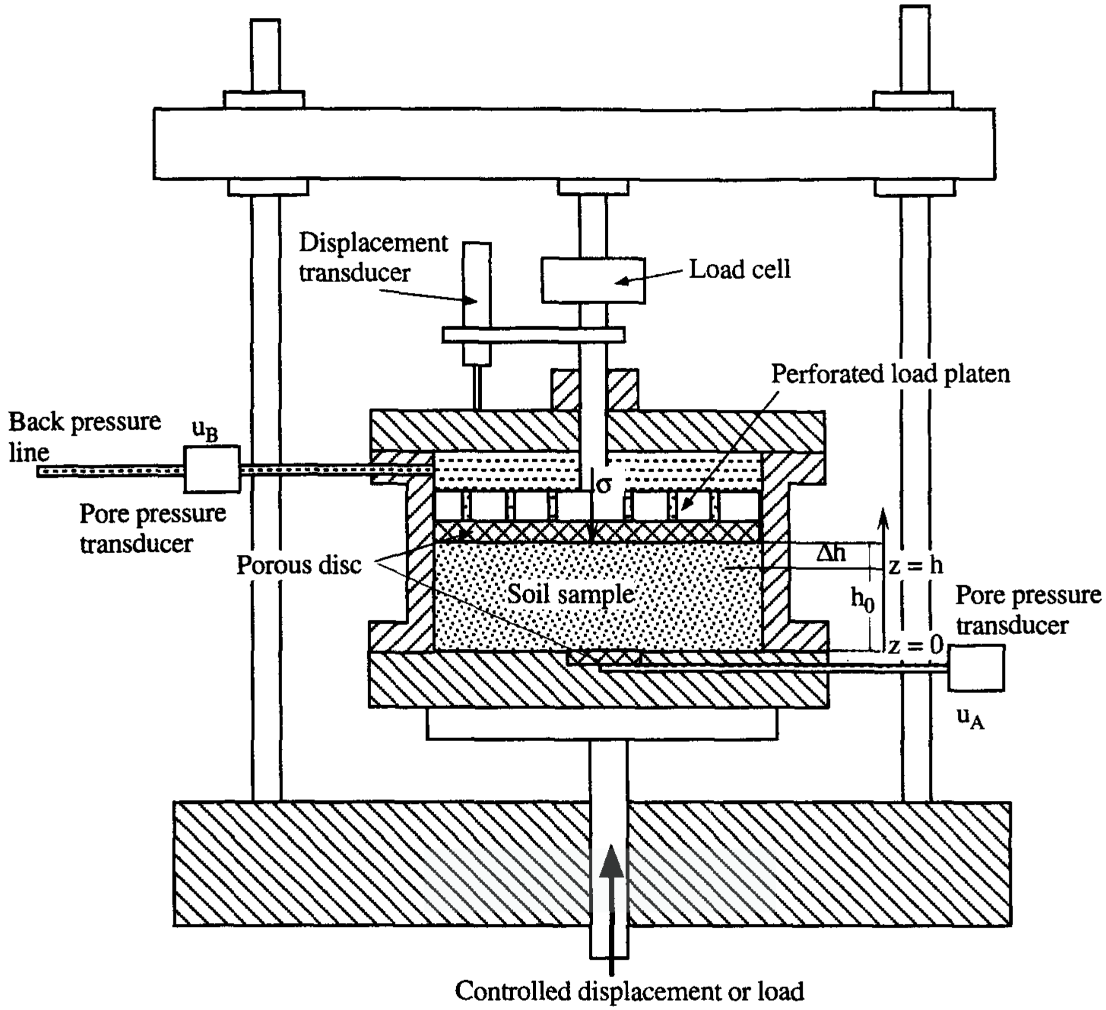
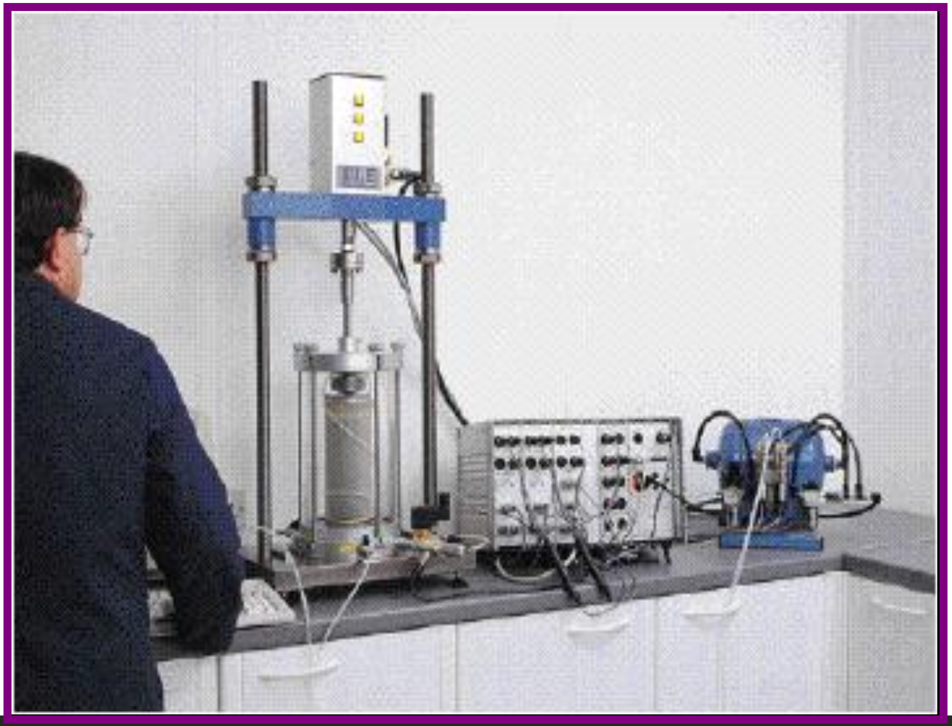


Figure 21 Experimental setup for alternate consolidation test (after Head, 1986).

Triaxial test (CU test)

Consolidation parameters could also be found from the results of Triaxial testing under during the consolidation stage (CU Test)



Triaxial test (CD)

Field measurements

- Piezocone/CPTU
- In-situ permeability test (constant and falling head, Wilkinson, 1968)
- Field Consolidation (Clarke et.al., 1979)

Piezocone Test/CPTU

Standard Procedure: ASTM D3441-79

Cone Penetration Test (CPT): International reference test procedure.

Int'l symposium on Penetration Testing, ISOPT-1 Florida, 1998

Output of CPTU:

q_c = *cone resistance*

f_s = *friction resistance*

R_f = *friction ratio*

u = *porewater pressure*

Piezocone Test/CPTU

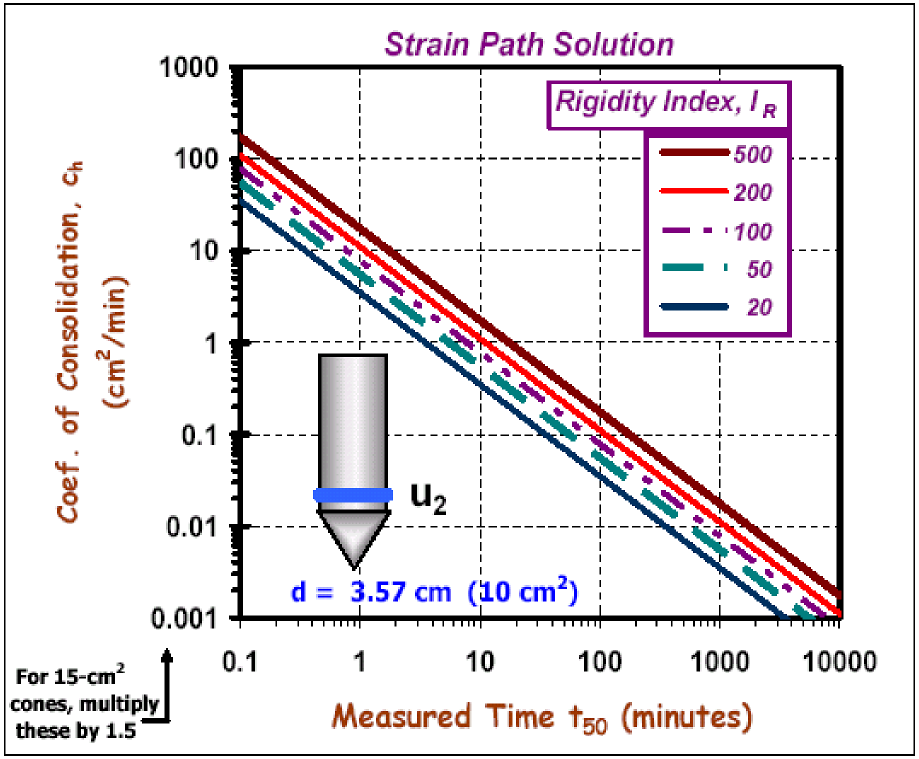
The reading of u can be used to calculate coef of horizontal consolidation c_h (Tortesson, 1977) where:

$$c_h = \frac{r^2 T}{t}$$

r = radius of the cone

T = time factor, depend on the degree of dissipation and rigidity index E_u/c_u

Use this graph to find c_h based on t_{50}



Piezocone Test/CPTU

Use the table to find values of r^2T
(where $r = d/2 = 1.78$cm)

(cylindrical/axy-simmetric solution)

Degree of dissipation	20%	50%
E/Cu = 500	1.07	13.59
400	0.94	11.30
300	0.77	8.91
200	0.57	7.34
100	0.43	4.33

Summary of lecture

1. Consolidation is the time-dependent settlement of soils by the expulsion of water from the voids.
2. When a load is applied to a saturated soil, all of the applied stress is supported initially by the pore water (initial excess pore water pressure), i.e., at $t = 0$, $\Delta\upsilon_o = \Delta\sigma_z$ or $\Delta u_o = \Delta p$. The change in effective stress is zero ($\Delta\sigma'_z = 0$).
3. If drainage of pore water is permitted, the initial excess pore water pressure decreases and soil settlement (Δz) increases with time, i.e., $\Delta u(t) < \Delta u_o$ and $\Delta z > 0$. The change in effective stress is $\Delta\sigma'_z = \Delta\sigma_z - \Delta u(t)$.
4. When $t \rightarrow \infty$, the change in volume and the change in excess pore water pressure of the soil approach zero, i.e., $\Delta V \rightarrow 0$ $\Delta u_o \rightarrow 0$. The change in vertical effective stress is $\Delta\sigma'_z = \Delta\sigma_z$.
5. Soil settlement is not linearly related to time except very early in the consolidation process.
6. The change in volume of the soil is equal to the volume of initial excess pore water expelled.

7. The change in volume of the soil is related to the change in void ratio as follows

$$\Delta V = V \frac{\Delta e}{1 + e_o}$$

For one-dimensional consolidation, the vertical settlement is

$$\Delta z = H \frac{\Delta e}{1 + e_o}$$

8. The rate of settlement depends on the permeability of the soil, the length of the drainage path and the thickness of the soil layer.
9. The changes in void ratio or settlement are not linearly related to vertical effective stress.
10. The amount of settlement depends on the history of loading the soil and the vertical effective stress to be applied. The history of loading is described by the over-consolidation ratio - the ratio of the past vertical effective stress to the current vertical effective stress.

Thanks for your attention