Consolidation OF SOILS

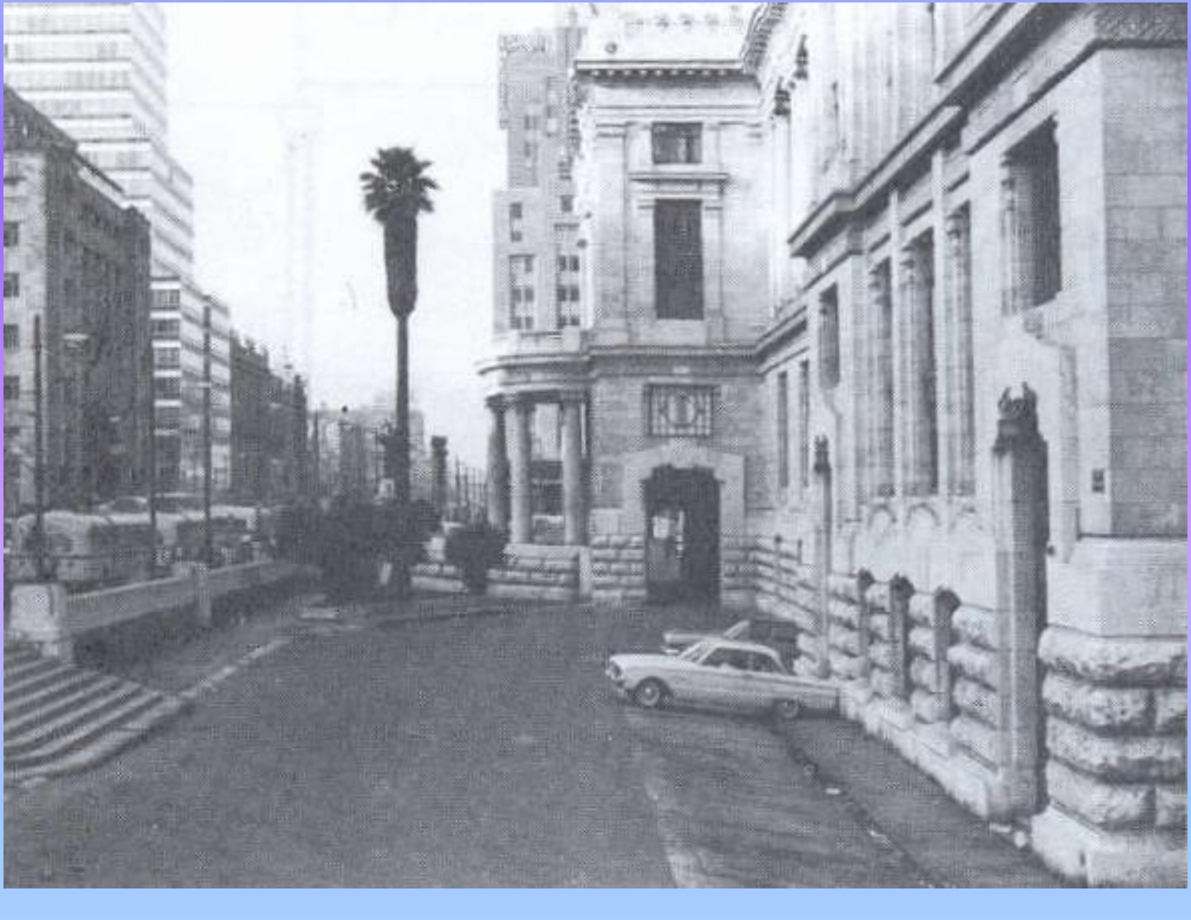
- *Decrease in volume of a soil due to*
  - *Compression of solid particles*
  - *Compression of water in the voids*
  - *Expulsion of water in the voids*
  - *Compression of air in the voids*
  - *Expulsion of air in the voids*
- *Consolidation–*

Decrease in volume of a saturated soil mass

due to expulsion of water in the voids,

under steady static pressure

How much would the completed building settle and would it settle uniformly?



This building in Mexico has settled 3.6 m without damage !

Compaction	Consolidation
Rapid process of volume reduction	*Gradual process of volume reduction*
By mechanical means such as rolling, tamping and vibration *{loading of short duration}*	*By sustained, static loading*
Reduction in volume due to expulsion of air from the voids	*Reduction in volume due to expulsion of water from the voids*
Artificial process done to increase the density of soil	*Natural process caused by the weight of buildings and other structures*

- *Initial consolidation:*
  - *Reduction in volume immediately after the application of load*
  - *Due to*

    expulsion & compression of air in voids

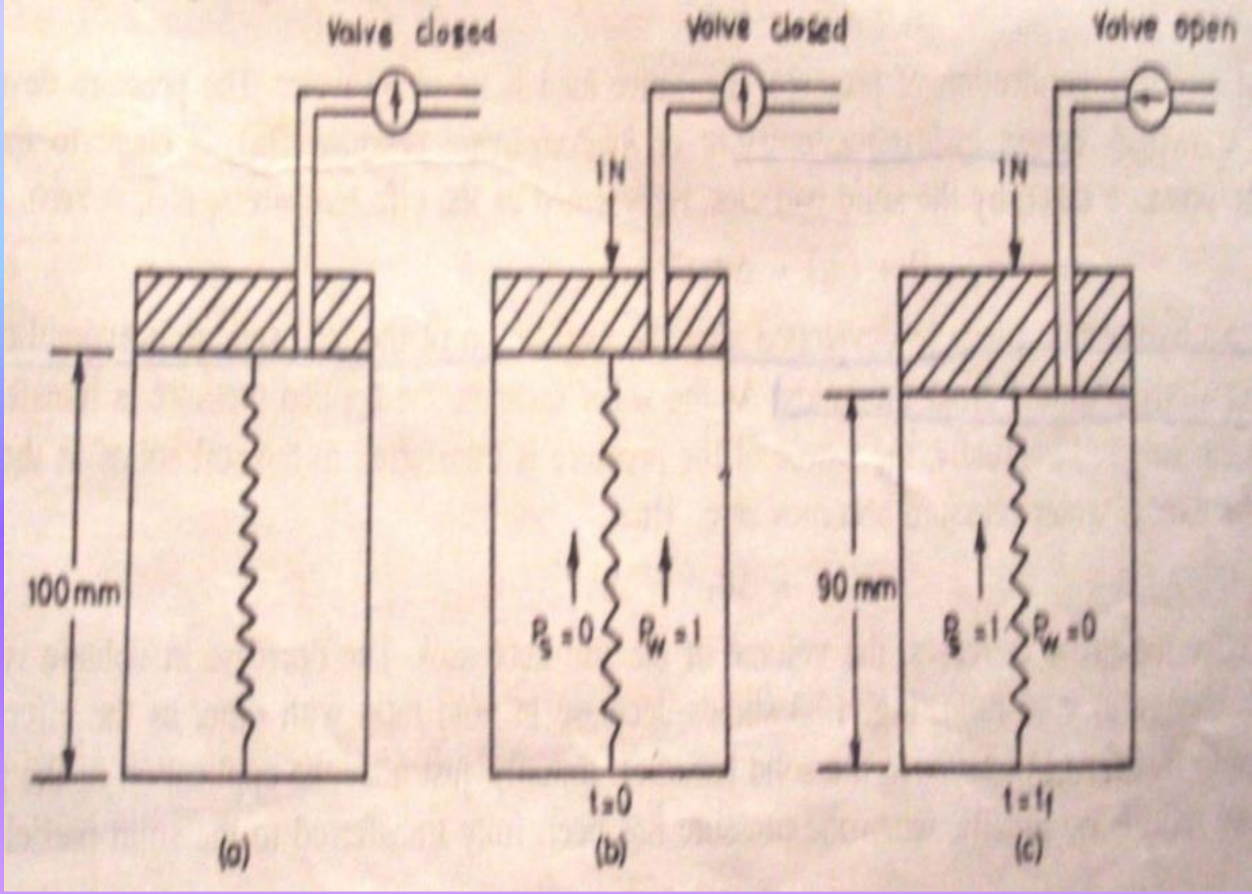
    + compression of solid particles

- ***Primary consolidation***

- *Secondary consolidation*
  - *Reduction in volume continues even after primary consolidation is complete*
  - *At slow rate*
  - *Due to plastic readjustment of solid particles and the adsorbed water to the new stress system*

- *Primary consolidation – most important component in consolidation settlement of a clay soil*

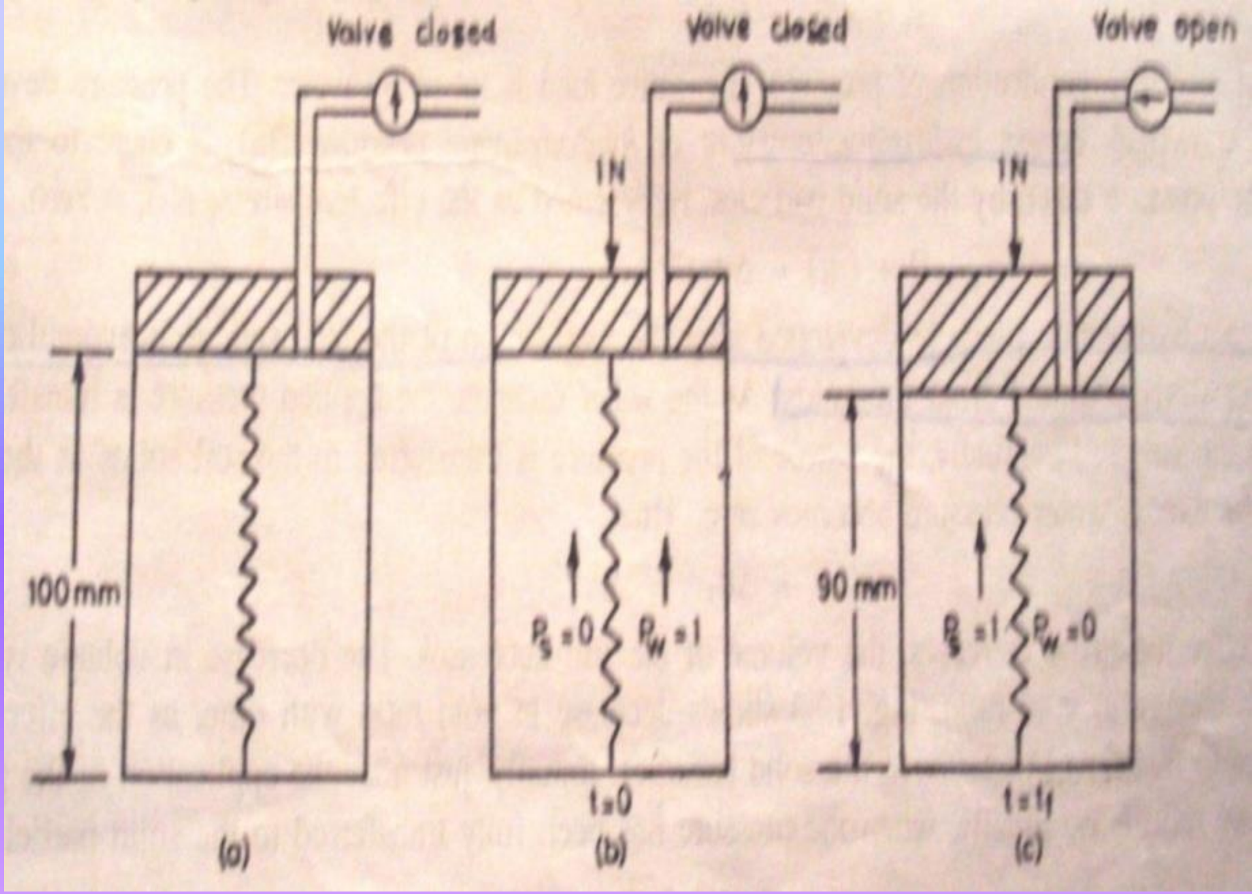
Spring analogy



Spring analogy

Fig. (b)

$P_w = P$; $P_s = 0.0$

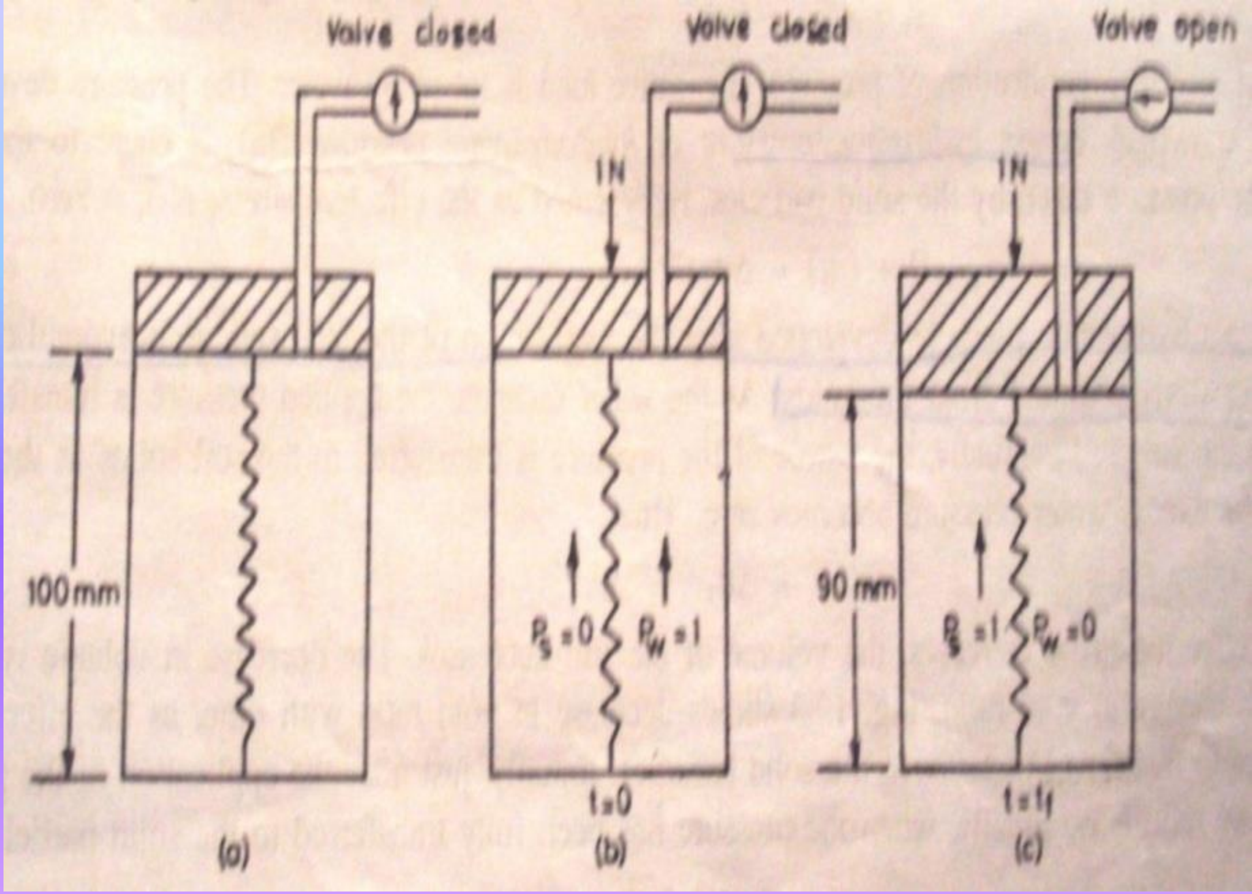


Spring analogy

Fig. (b)

$P_w = P$; $P_s = 0.0$

$Pw = P - \Delta$; $Ps = \Delta$



Spring analogy

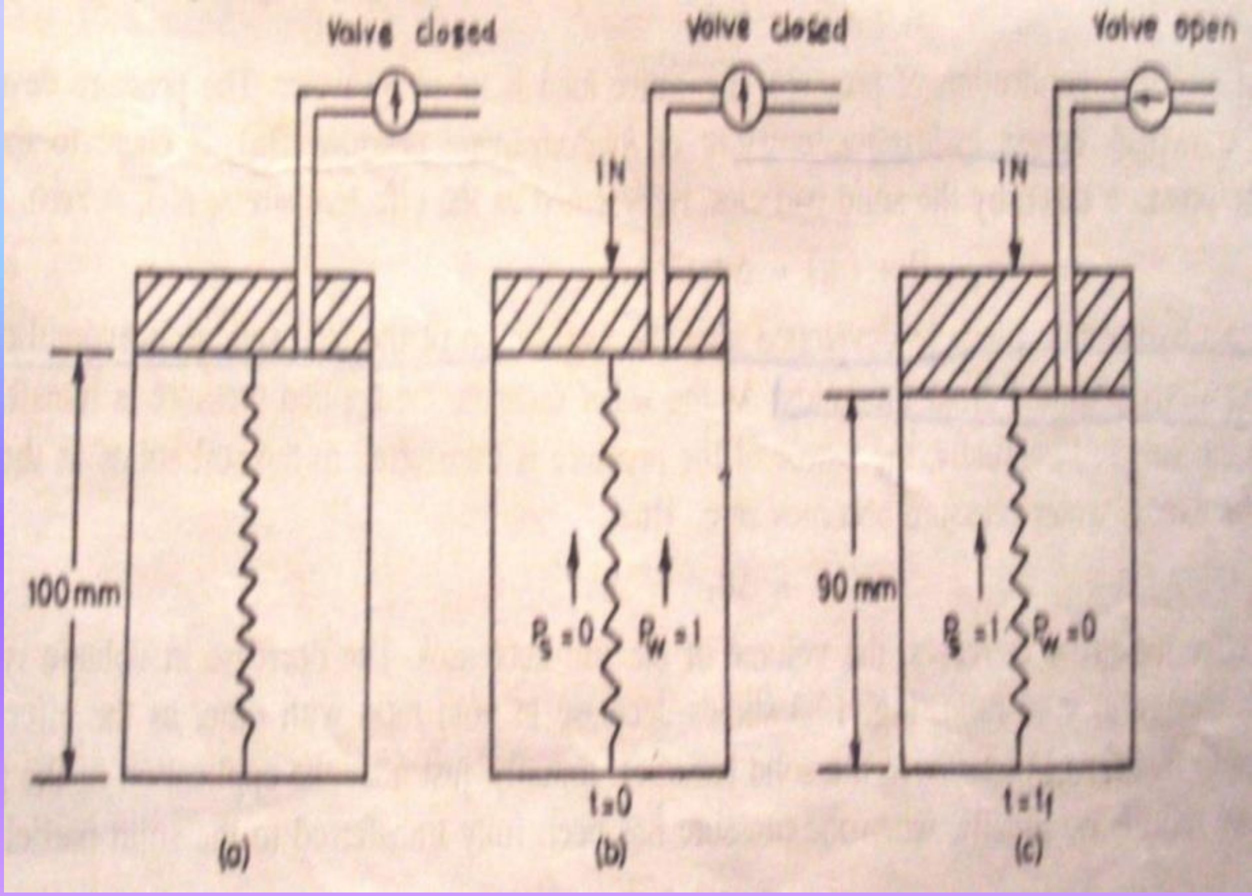
Fig. (b)

$P_w = P$; $P_s = 0.0$

$Pw = P - \Delta$; $Ps = \Delta$

Fig. (c)

$P_w = 0.0$; $P_s = P$



- **Solid particles** – analogous to spring
- **Water in voids** -analogous to water in cylinder
- **Permeability of soil** -valve in piston
- **Pore water pressure** – pressure carried by water in cylinder
- **Effective stress in soil** – stress carried by spring

Behaviour of saturated soil under sustained loading

At the instant when the loading is applied on the soil,

the entire pressure [σ, p] is taken up by water.

excess pore pressure, $u = \sigma$ &

effective stress, $\sigma' = 0.0$

As water flows out of the soil voids,

the stress would be shared by the solid particles and porewater .

excess pore pressure, $u = \Delta$

effective stress, $\sigma' = \sigma - \Delta$

Once the entire pressure is transferred to soil solids,

primary consolidation ceases .

At this stage, excess pore pressure, $u = 0.0$ &

effective stress, $\sigma' = \sigma$

Consolidation Test

Consolidation cell

oedometer

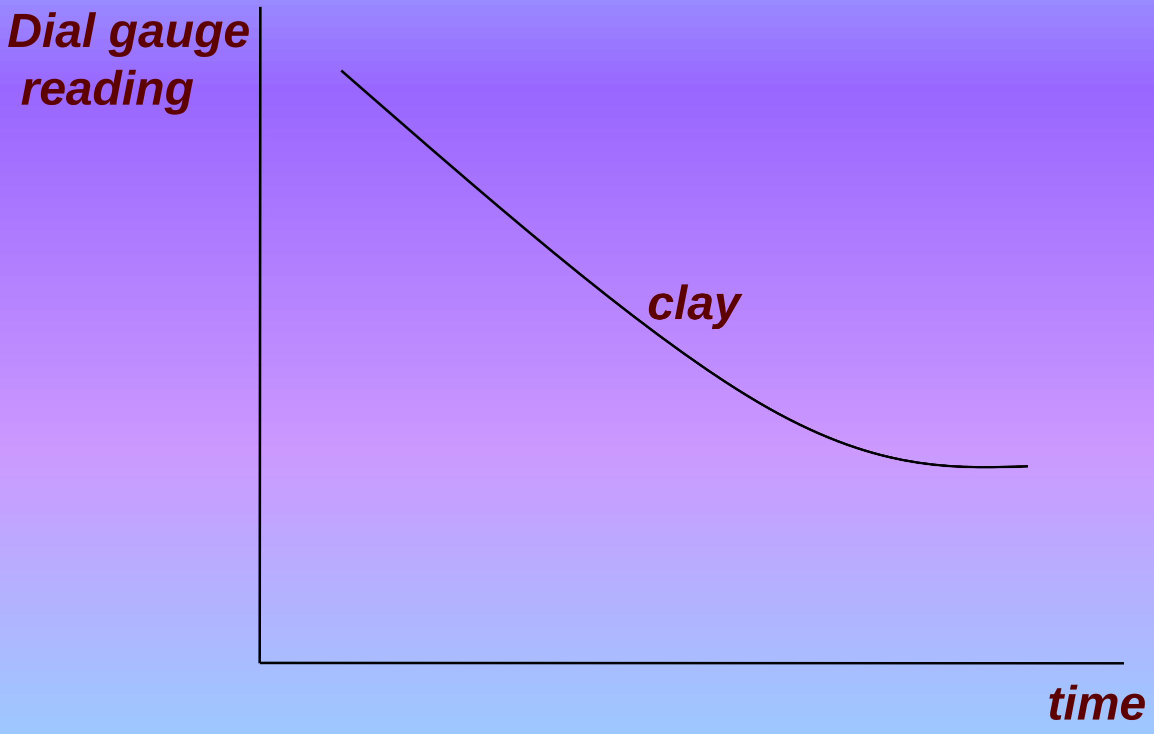
Apparatus

- *Consolidation cell-floating or fixed ring cell*

Initial seating pressure – 5kN/m^2

Test results

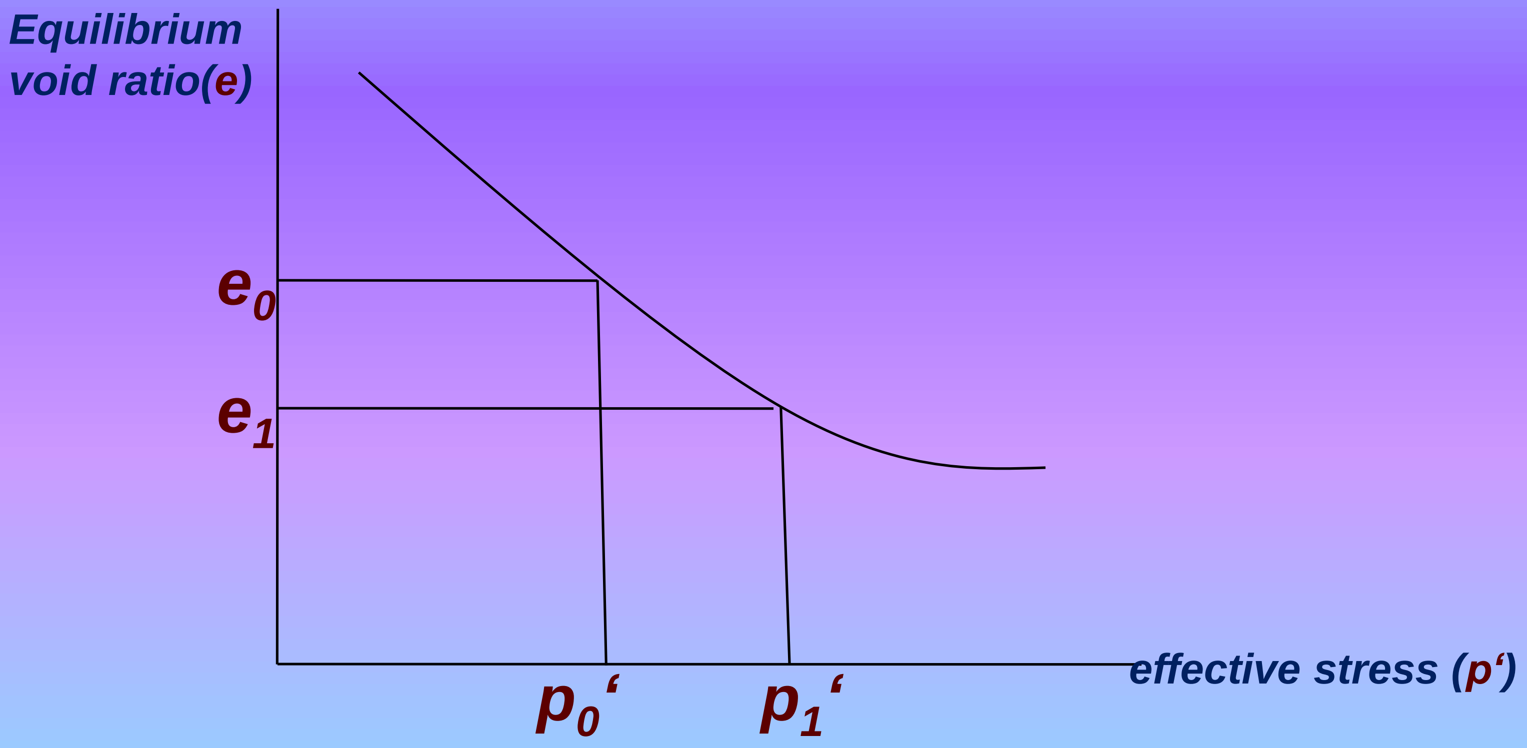
1. ## Dial gauge reading – time plot



Useful to obtain rate of consolidation in the field

Test results

2. Equilibrium void ratio (e)-effective stress (p') plot

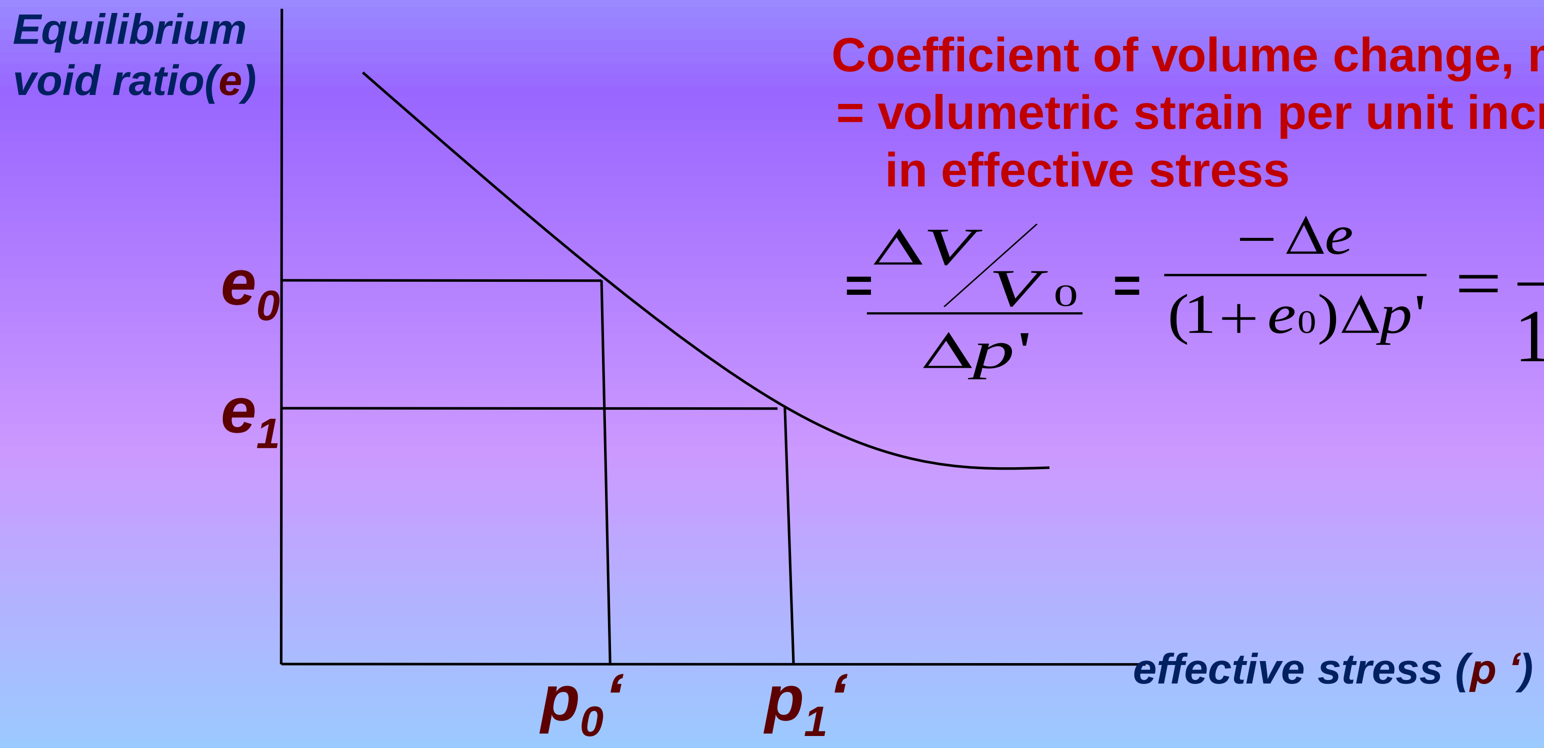


Useful to obtain the magnitude of consolidation settlement in field

Test results

2. *Equilibrium void ratio (e)-effective stress (p') plot*

Coefficient of compressibility, $a_v = \dfrac{-\Delta e}{\Delta p'}$



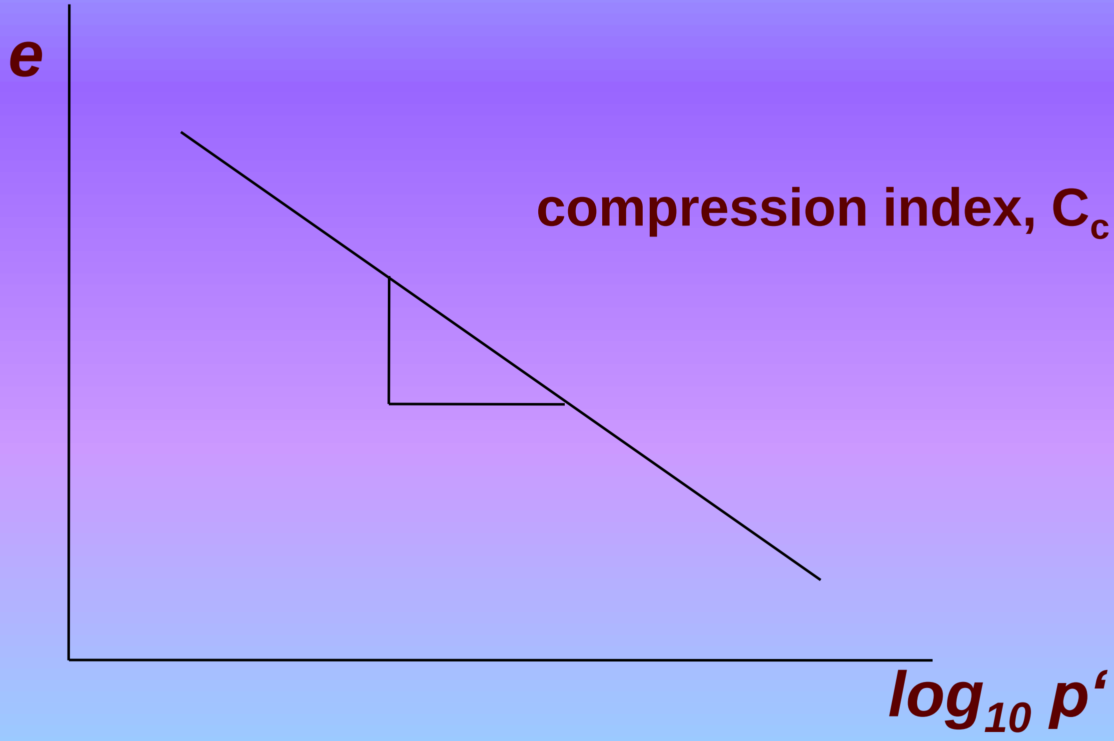
Coefficient of volume change, m_v
= volumetric strain per unit increase in effective stress

$$= \frac{\Delta V / V_0}{\Delta p'} = \frac{-\Delta e}{(1+e_0)\Delta p'} = \frac{a_v}{1+e_0}$$

***Δ H = settlement in field* = $m_v \Delta p' H$**

Test results

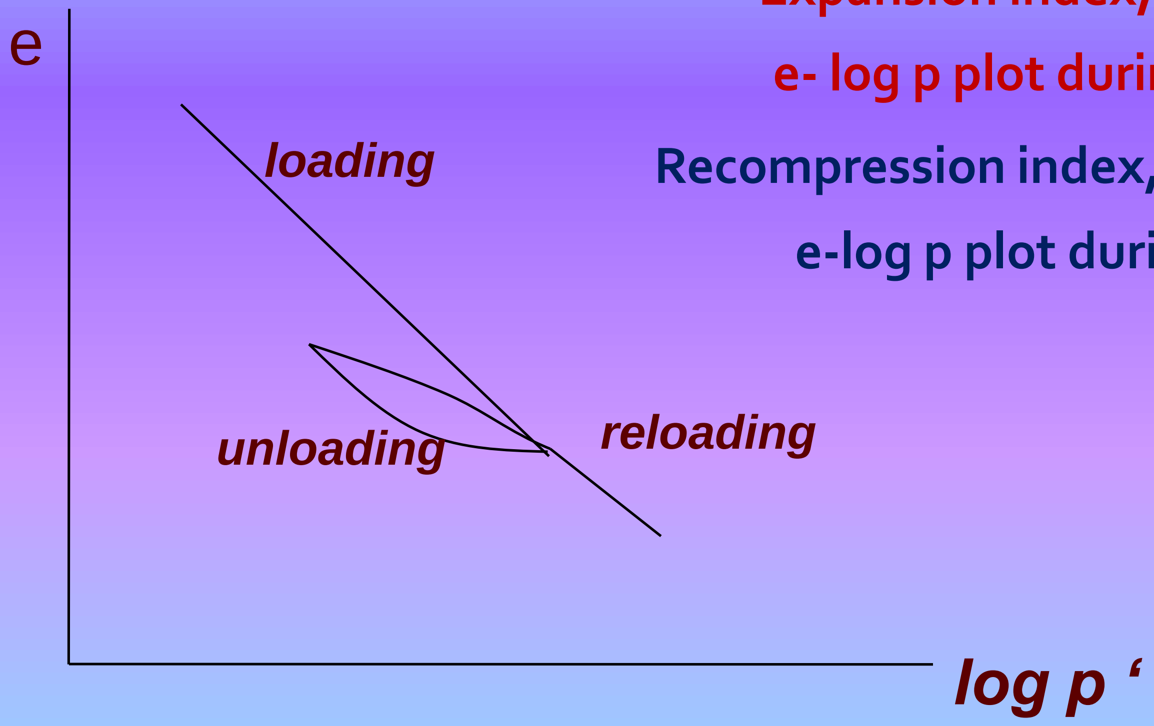
3. ***e-log(p') graph***



compression index, $C_c = \dfrac{-\Delta e}{\log\{p_1'/p_0'\}}$

ΔH = settlement in field = $C_C/(1+e_0)$. $H.\log_{10}\{(p_o'+\Delta p)/p_0'\}$

4. *Unloading and reloading plot*



Expansion index, C_e = Slope of e- log p plot during unloading

Recompression index, Cr =Slope of e-log p plot during reloading

Determination of equilibrium void ratio

Height of solids method

$$H_s = \frac{V_s}{A} = \left(\frac{W_s}{G\gamma_w}\right)\frac{1}{A}$$

Hs – height of solids
Vs – volume of solids
Ws – dry mass of solids
G-specific gravity
A-c/s area of specimen

$$e = \frac{V - V_s}{V} = \left(AH - AH_s\right)\frac{1}{AH_s} = \frac{H - H_s}{H_s}$$

Determination of equilibrium void ratio

Change in void ratio method

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

Final settlement of normally consolidated clay

$$\Delta H = H_o\left(\frac{\Delta e}{1+e_o}\right)$$ .....(1)

$$S_f = H_o\left(\frac{\Delta e}{1+e_o}\right)$$ .....(2)

We know, compression index,

$$C_c = -\frac{\Delta e}{\log_{10}\left(\frac{\sigma_o'+\Delta\sigma'}{\sigma_o'}\right)}$$ ....(3)

Substituing for Δe from (3) in (2)

$$S_f = \frac{C_c}{1+e_o} H_o \log_{10}\left(\frac{\sigma_o'+\Delta\sigma'}{\sigma_o'}\right)$$

Change in void ratio method

$H=24mm$ $A=50\ cm^2$ $V=120cm3$ $G=2.7$ $w_f=32\%$

Applied pressure, p [kPa]	Dial gauge reading	Change in thickness, ΔH (mm)	Specimen height, H (mm)	Change in void ratio, Δe	void ratio e
0	82				
10	104				
20	152				↑
50	260				
100	[illegible]				

Change in void ratio method

H=24mm, A=50 cm2, V=120cm3, Hf=17.75mm, w=32%,Δe=0.105ΔH

Applied pressure p kPa	Dial gauge reading	Change in thicknessΔH (mm)	Specimen height H (mm)	Change in void ratio Δe	void ratio e
0	82				
10	104	-0.22			
20	152	-0.48			
50	260	-1.08			
100	424	-1.64			
200	578	-1.54			
400	730	-1.52			
800	851	-1.21			
0	707	-1.44			

Change in void ratio method

H=24mm, A=50 cm^2, V=120cm3, H_f=17.75mm, w=32%,$\Delta e=0.105\Delta H$

Applied pressure p kPa	Dial gauge reading	Change in thicknessΔ H (mm)	Specimen height H (mm)	Change in void ratio Δe	void ratio e
0	82		24.00		
10	104	-0.22	23.78		
20	152	-0.48	23.30		
50	260	-1.08	22.22		
100	424	-1.64	20.58		
200	578	-1.54	19.04		
400	730	-1.52	17.52		
800	851	-1.21	16.31		
0	707	-1.44	17.75		

Change in void ratio method

H=24mm, A=50 cm^2, V=120cm3, H_f=17.75mm, w=32%,$\Delta e=0.105\Delta H$

Applied pressure p kPa	Dial gauge reading	Change in thicknessΔH (mm)	Specimen height H (mm)	Change in void ratio Δe	void ratio e
0	82		24.00		
10	104	-0.22	23.78	-0.023	
20	152	-0.48	23.30	-0.050	
50	260	-1.08	22.22	-0.114	
100	424	-1.64	20.58	-0.172	
200	578	-1.54	19.04	-0.162	
400	730	-1.52	17.52	-0.160	
800	851	-1.21	16.31	-0.127	
0	707	-1.44	17.75	-0.151	

Change in void ratio method

H=24mm, A=50 cm^2, V=120cm3, H_f=17.75mm, w=32%,$\Delta e=0.105\Delta H$

Applied pressure p kPa	Dial gauge reading	Change in thicknessΔ H (mm)	Specimen height H (mm)	Change in void ratio Δe	void ratio e
0	82		24.00		
10	104	-0.22	23.78	-0.023	
20	152	-0.48	23.30	-0.050	
50	260	-1.08	22.22	-0.114	
100	424	-1.64	20.58	-0.172	
200	578	-1.54	19.04	-0.162	
400	730	-1.52	17.52	-0.160	
800	851	-1.21	16.31	-0.127	
0	707	-1.44	17.75	-0.151	0.864 ↑

Change in void ratio method

H=24mm, A=50 cm^2, V=120cm3, H_f=17.75mm, w=32%,$\Delta e=0.105\Delta H$

Applied pressure p kPa	Dial gauge reading	Change in thicknessΔ H (mm)	Specimen height H (mm)	Change in void ratio Δe	void ratio E
0	82		24.00		1.521
10	104	-0.22	23.78	-0.023	1.498
20	152	-0.48	23.30	-0.050	1.448
50	260	-1.08	22.22	-0.114	1.334
100	424	-1.64	20.58	-0.172	1.162
200	578	-1.54	19.04	-0.162	1.000
400	730	-1.52	17.52	-0.160	0.840
800	851	-1.21	16.31	-0.127	0.713
0	707	+1.44	17.75	+0.151	0.864 ↑

Change in void ratio method

H=24mm, A=50 cm2, V=120cm3, Hf=17.75mm, w=32%,Δe=0.105ΔH

Applied pressure p kPa	Dial gauge reading	Change in thicknessΔ H (mm)	Specimen height H (mm)	Change in void ratio Δe	void ratio e
0	58				
10	66				
20	76				
50	138				
100	233				
200	341				
400	447				
600	548				
800	550				
1000	578				
0	438				

Change in void ratio method

H=24mm, A=50 cm2, V=120cm3, Hf=17.75mm, w=32%,Δe=0.105ΔH

Applied pressure p kPa	Dial gauge reading	Change in thicknessΔH (mm)	Specimen height H (mm)	Change in void ratio Δe	void ratio e
0	58				
10	66	-0.08			
20	76	-0.10			
50	138	-0.62			
100	233	-0.95			
200	341	-1.08			
400	447	-1.06			
600	548	-1.01			
800	550	-0.02			
1000	578	-0.28			
0	438	1.40			

Change in void ratio method

H=24mm, A=50 cm2, V=120cm3, Hf=17.75mm, w=32%,∆e=0.105∆H

Applied pressure p kPa	Dial gauge reading	Change in thickness∆ H (mm)	Specimen height H (mm)	Change in void ratio ∆e	void ratio e
0	58		24.00		
10	66	-0.08	23.92		
20	76	-0.10	23.82		
50	138	-0.62	23.20		
100	233	-0.95	22.25		
200	341	-1.08	21.17		
400	447	-1.06	20.11		
600	548	-1.01	19.10		
800	550	-0.02	19.08		
1000	578	-0.28	18.80		
0	438	1.40	20.20		

Change in void ratio method

H=24mm, A=50 cm2, V=120cm3, Hf=17.75mm, w=32%,$\Delta e=0.105\Delta H$

Applied pressure p kPa	Dial gauge reading	Change in thickness ΔH (mm)	Specimen height H (mm)	Change in void ratio Δe	void ratio e
0	58		24.00	10.55	
10	66	-0.08	23.92	10.47	
20	76	-0.10	23.82	10.37	
50	138	-0.62	23.20	9.75	
100	233	-0.95	22.25	9.5	
200	341	-1.08	21.17	7.72	
400	447	-1.06	20.11	6.66	
600	548	-1.01	19.10	5.65	
800	550	-0.02	19.08	5.63	
1000	578	-0.28	18.80	5.35	
0	438	1.40	20.20	6.75	

Change in void ratio method

H=24mm, A=50 cm2, V=120cm3, Hf=17.75mm, w=32%,Δe=0.105ΔH

Applied pressure p kPa	Dial gauge reading	Change in thicknessΔ H (mm)	Specimen height H (mm)	Change in void ratio Δe	void ratio e
0	58		24.00	10.55	0.786
10	66	-0.08	23.92	10.47	0.778
20	76	-0.10	23.82	10.37	0.771
50	138	-0.62	23.20	9.75	0.725
100	233	-0.95	22.25	9.5	0.656
200	341	-1.08	21.17	7.72	0.575
400	447	-1.06	20.11	6.66	0.495
600	548	-1.01	19.10	5.65	0.420
800	550	-0.02	19.08	5.63	0.418
1000	578	-0.28	18.80	5.35	0.398
0	438	1.40	20.20	6.75	0.502

Normally consolidated, over-consolidated and under-consolidated states of clay

OC state: **Soil had been subjected in the past to a pressure greater than the present (existing) overburden pressure**

Overconsolidation ratio: **max. pressure to which soil had been subjected to, in the past /present pressure**

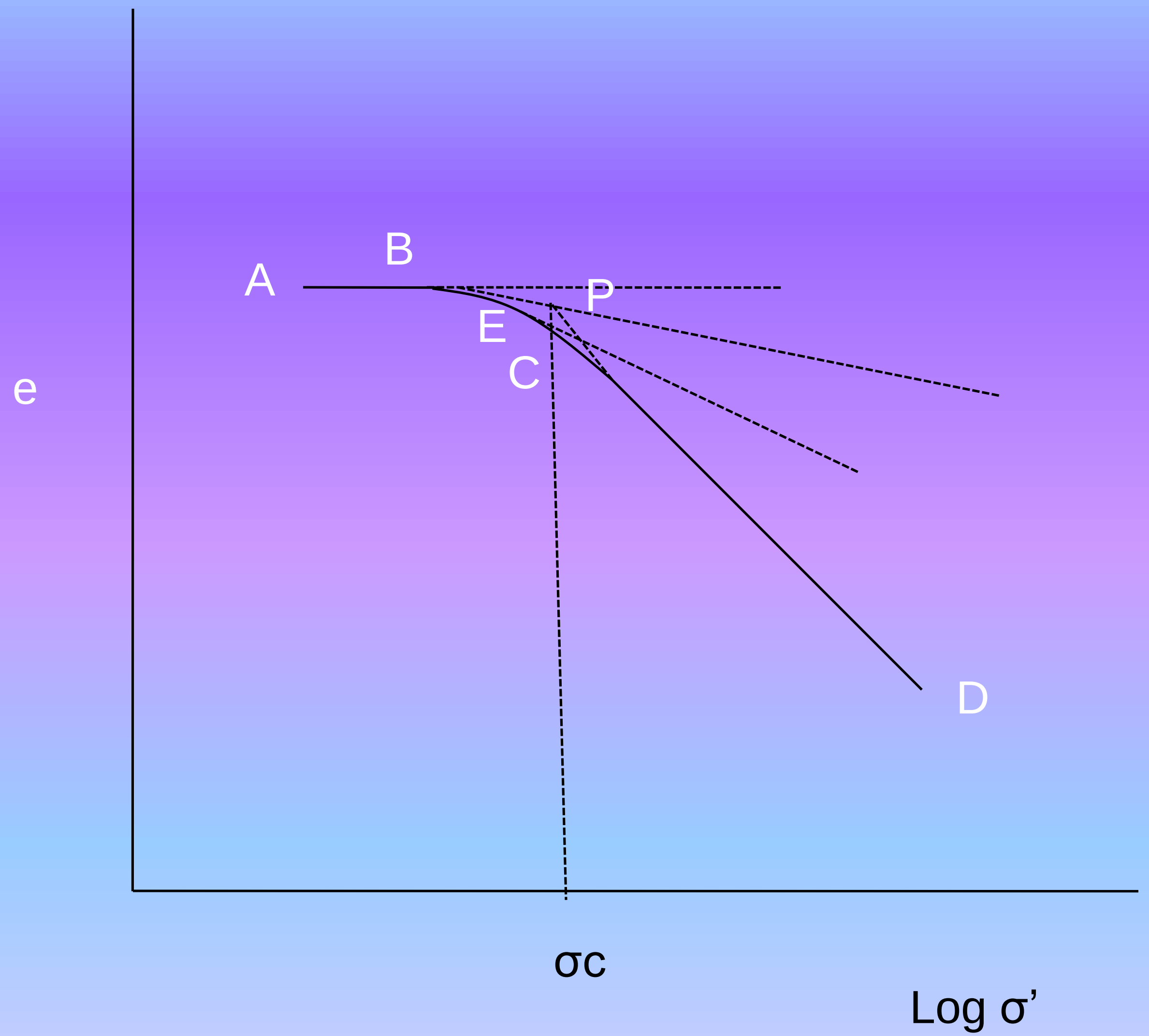
UC state: **Soil has not undergone complete consolidation under the existing overburden pressure.**

NC state: **Soil has not been subjected in the past to a pressure greater than the present(existing) overburden pressure; At the same time. it has got fully consolidated under the existing overburden pressu**

Causes of preconsolidation

- Overburden removed by erosion
- Demolished structures
- Melting of glaciers
- Dessication of clay deposits
- Downward seepage forces
- Tectonic forces
- Capillary forces acted in the past

Preconsolidation pressure



Terzaghi's theory of one-dimensional Consolidation

- *To determine the rate of consolidation of saturated soil subjected to sustained static load*

✓Soil --- homogeneous, isotropic
✓Fully saturated
✓Solid particles and water --- incompressible
✓Coeff. of permeability --- constant
✓Darcy's law is valid
✓Drainage of water --- vertical
✓Consolidation is one-dimensional
✓Low permeability of soil --- time lag
✓a_v and m_v are constants

Basic differential equation of one dimensional consolidation

$$c_v \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t}$$

where C_v is the coefficient of consolidation

$$c_v = \frac{k}{m_v \gamma_w}$$

- *Solution of equation of 1D consolidation shows that the average degree of consolidation, U = f(Time factor, Tv)*

$$T_v = \frac{\pi}{4} U^2$$ **U<0.60**

$$T_v = 1.781 - 0.933 \log_{10} (100 - U\%)$$ **U>0.60**

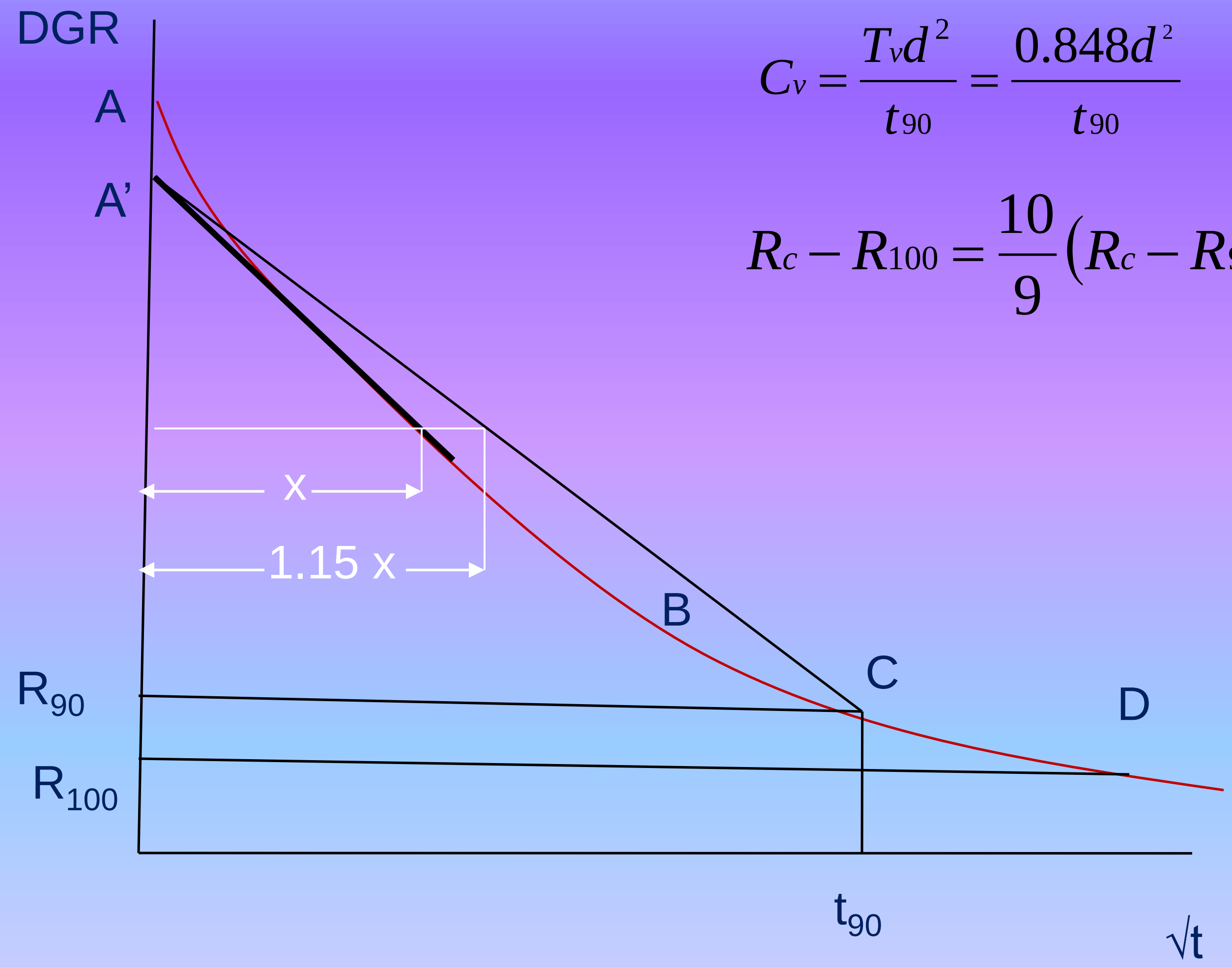
$$T_v = \frac{C_v t}{d^2}$$

U = Settlement at time, t / ultimate settlement

Cv – coefficient of consolidation
t – time elapsed since the commencement of consolidation
d – drainage path

Determination of coefficient of consolidation

Square root of time method:

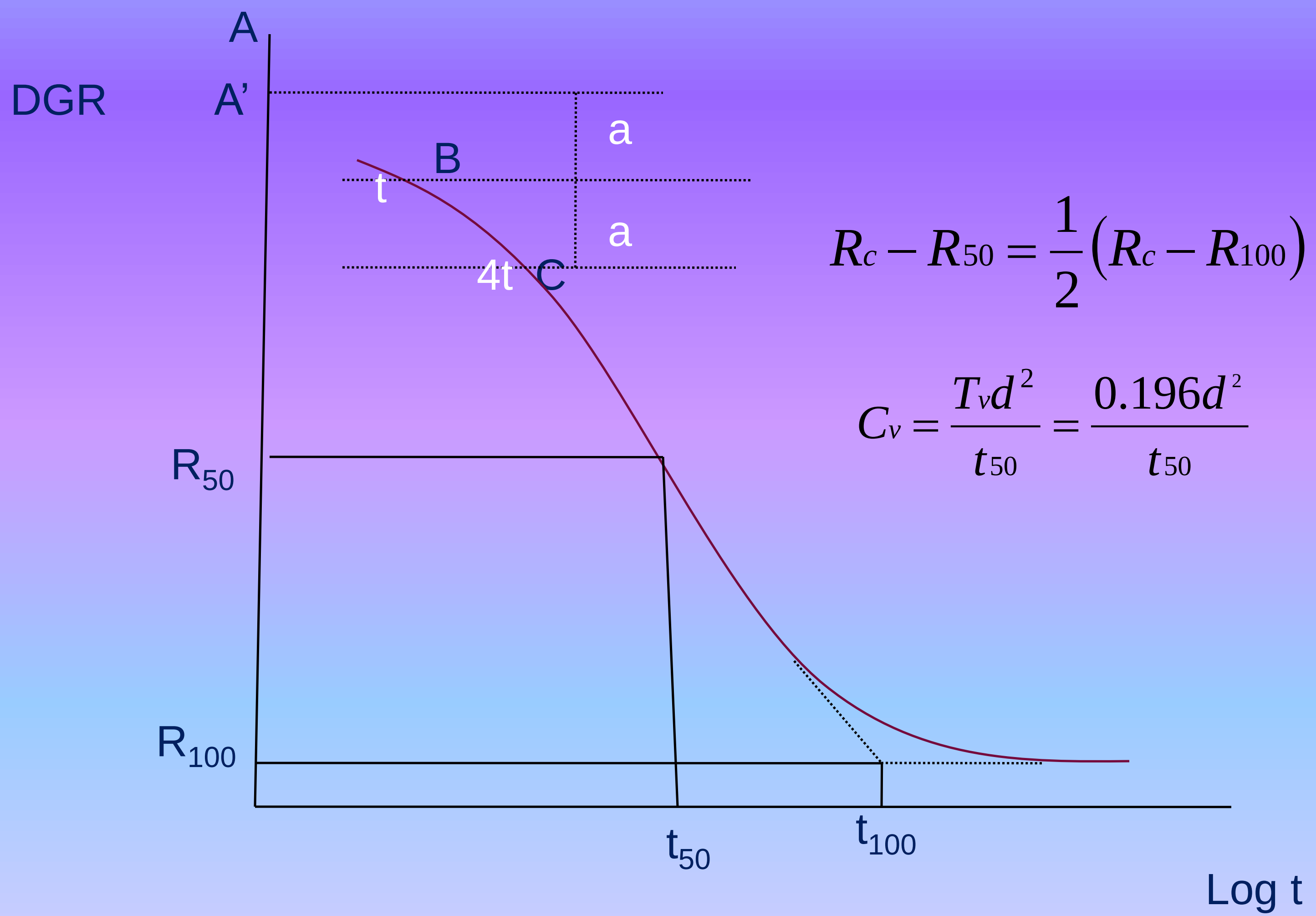


$$C_v = \frac{T_v d^2}{t_{90}} = \frac{0.848 d^2}{t_{90}}$$

$$R_c - R_{100} = \frac{10}{9}\left(R_c - R_{90}\right)$$

Determination of coefficient of consolidation

Logarithm of time method:



$$R_c - R_{50} = \frac{1}{2}\left(R_c - R_{100}\right)$$

$$C_v = \frac{T_v d^2}{t_{50}} = \frac{0.196 d^2}{t_{50}}$$

Compression Ratios

1. Initial compression ratio:

$$r_i = \frac{R_o - R_c}{R_o - R_f}$$

2. Primary compression ratio:

$$r_p = \frac{R_c - R_{100}}{R_o - R_f}$$

3. Secondary compression ratio:

$$r_s = \frac{R_{100} - R_f}{R_o - R_f}$$