Consolidation

Consolidation

When a load is applied to a soil mass, the soil compresses. This compression of soil may be due to any of the following factors or affect of these factors.

- Distortion (Change of the Shape of Soil grains)
- Compression of air and water in the soil voids
- Reduction of volume due to expulsion of water/ air from the voids

Under usual range of loading applied on a soil mass through the foundations of civil engineering structures, the distortion is small and negligible.

Fine grain soil in nature are generally saturated and the amount of air is very small and insignificant.

Water being incompressible fluid dose not cause significant deformation in soil under practical range of loading. Thus the deformation in saturated soil is mainly is due to reduction in volume brought about by the expulsion of water from the voids. This phenomenon is termed as Consolidation

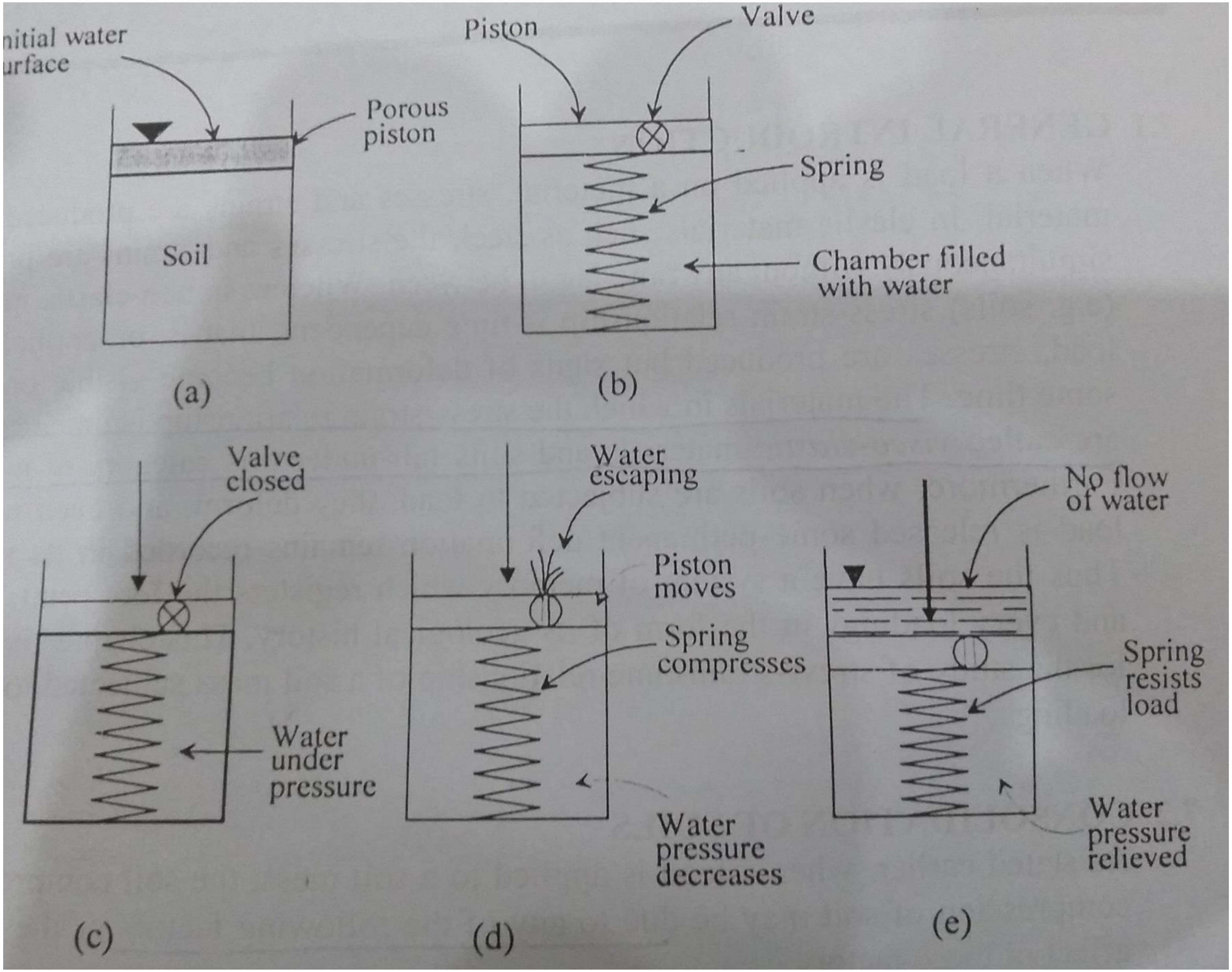
The consolidation process is generally a drainage process

Consolidation Model (Hydro Mechanical Analog)

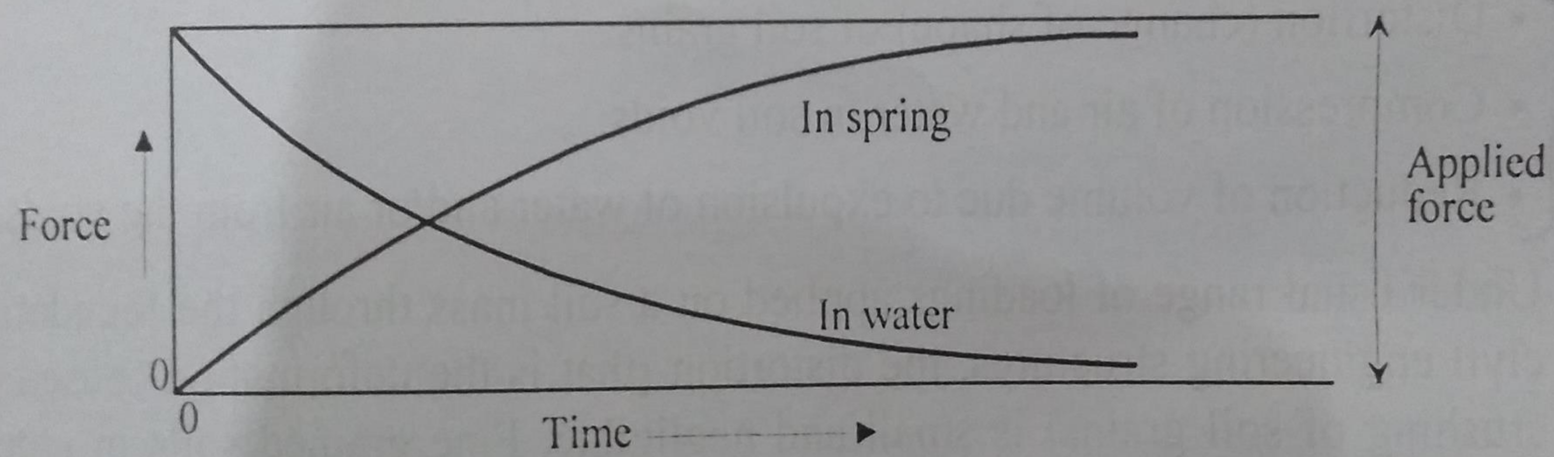
To understand the mechanism of consolidation consider the following Figure.
Figure represent a saturated cylinder of soil mass.
The porous piston in this figure (a), permits load to be applied to the soil allowing escape of water through the pores of the piston.
Figure (b), shows a hydro mechanical analog in which the spring represents the soil mineral skeleton and water in the cylinder represents the pore fluid in the soil mass. The soil permeability is represents by the valve attached to the otherwise impermeable piston.
In Figure (c), an external stress is applied on the piston with the valve closed. Essentially all the applied stress is resisted by an increase in the pore water pressure known as hydrostatic excess pore water pressure (neutral pressure). At this stage, following relationship exists:

That is total stress = Pore pressure

$$\Delta\delta_v = \Delta_u$$



nitial water
urface
Porous
piston
Soil
(a)
Piston
Valve
Spring
Chamber filled
with water
(b)
Valve
closed
Water
under
pressure
(c)
Water
escaping
Piston
moves
Spring
compresses
Water
pressure
decreases
(d)
No flow
of water
Spring
resists
load
Water
pressure
relieved
(e)



(f)

gure 7.1 *Hydromechanical analogy for load-sharing and consolidation. (a) ysical example. (b) Hydromechanical analog; initial condition. (c) Load plied with valve closed. (d) Piston moves as water escapes. (e) Equilibrium ith no further flow. (f) Gradual transfer of load.*

Consolidation Model (Hydro Mechanical Analog)

- Next open the valve, the fluid pressure within the cylinder will cause the water to flow through this valve. As the water escapes the spring starts to shorten due to transfer of load from the fluid to the spring.
- At that instant, load sharing between the water and the spring start.
- At any instant of time following relation holds good

$$\Delta\delta_v = \Delta\bar{\delta}_v + \Delta_u$$

- Where:
- $\Delta\delta_v$ = Total stress (Applied external pressure)
- $\Delta\bar{\delta}_v$ = The stress carried by the spring that by soil particles in general
- Δ_u = Pore water pressure also known as neutral stress

Consolidation Model (Hydro Mechanical Analog)

- From hydro mechanical analog following condition where obtained

1. The magnitude of deformation (settlement) in a consolidation is dependent only upon compressibility of the soil (i.e. Stiffness of the spring). The compressibility is expressed in term of coefficient of compression Index (C_c).
2. The rate of consolidation is a function of both permeability and compressibility of soil. The combined effect of them is represent by a coefficient of consolidation (C_v).
3. The time required for consolidation process is related to the following two factors.
   - The time should be directly proportional to the volume of water which must be squeezed out of the soil mass. This volume of water in turn be related to the " product of stress change, the compressibility of the soil and volume of soil".
   - The time must be inversely proportional to how fast the water can flow through the soil mass. On the other hand velocity of flow ="k.i" and the hydraulic gradient "i' is the head lost per unit length which the flow mus tflow

Consolidation Model (Hydro Mechanical Analog)

- Mathematically these two condition can be expressed as:

$$t = \frac{(\Delta\delta).(m_v).(H)}{(k).\frac{\left(\frac{\Delta\delta}{\gamma_w}\right)}{H}}$$

$$t = \frac{(m_v).(H)^2.\gamma_w}{(k)}$$

- Where:
- t = Time required to complete consolidation process
- $\Delta\delta$ = The time change in the applied stress causing consolidation
- m_v = Coefficient of volume change per drainage face
- H= Thickness of soil mass per drainage face
- K= Coefficient of permeability of the soil mass
- i = Hydraulic gradient = Head lost per unit length = $\frac{\left(\frac{\Delta\delta}{\gamma w}\right)}{H}$
-
- Let: Coefficient of consolidation = $C_v = \frac{k}{m_v.\gamma_w}$

Consolidation Model (Hydro Mechanical Analog)

- Then

$$t = \frac{T.H^2}{C_v}$$

$$T = \frac{t.C_v}{H^2}$$

- Where:
- T= Dimensionless constant known as time factor (values given in the following table)

U_{avg}	T
0.1	0.008
0.2	0.031
0.3	0.071
0.4	0.126
0.5	0.197
0.6	0.287
0.7	0.403
0.8	0.567
0.9	0.848
0.95	1.163
1.0	∞

U_{avg} = average degree of consolida

Consolidation Model (Hydro Mechanical Analog)

- The Relation tells us about that consolidation time

1. Increases with increasing coefficient of Volume change (m_v) of the soil mass
2. Decreases with increasing permeability coefficient (k).
3. Increases rapidly with increasing thickness of soil mass (H).
4. Is independent of the magnitude of the stress changes ($\Delta\delta$)

- For U < 60%

$$T = \frac{\pi}{4} . \left(\frac{U}{100} \right)^2$$

- For U > 60%

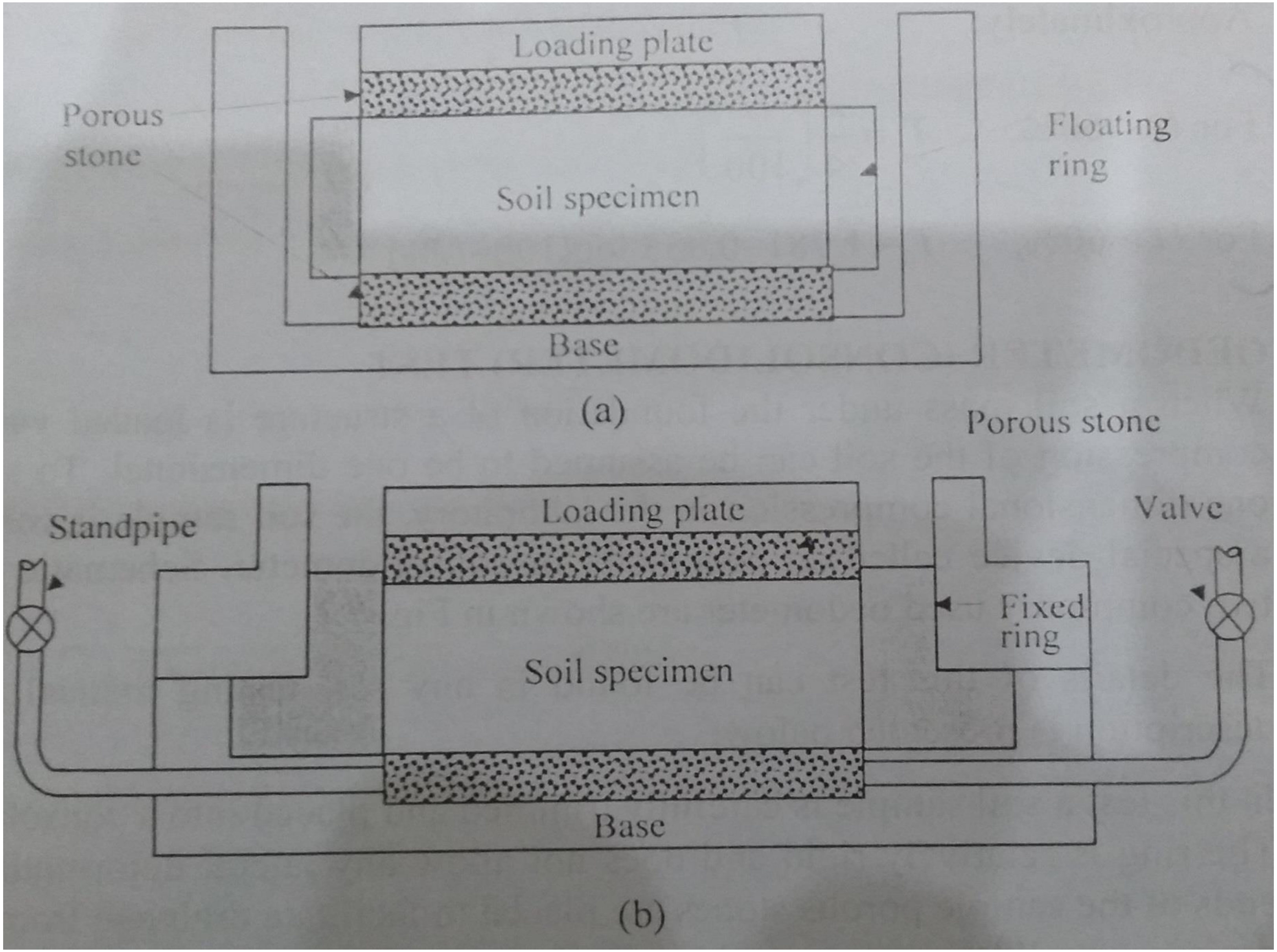
$$T = 1.781 - 0.933 \log(100 - U\%)$$

Oedometer (Consolidometer) Test

- When a soil mass under the foundation of a structure is loaded vertically, the compression of the soil can be assumed to be one dimensional. To simulate the one dimensional compression in laboratory, the soil sample is compressed in a special device called an Oedometer or Consolidometer.
- Schematic diagram of two of them is shown in Figure.
- **Test Procedure**
- In this test a soil sample is carefully trimmed and placed into a consolidation ring. The ring is relatively rigid and does not allow any lateral deformation. On both ends of the sample porous stones are placed to facilitate drainage from either ends during consolidation process. Usually "the ratio of the diameter to the height of the sample is between 2.5 to 5, depending upon the diameter of sampler.
- To study the relationship between load and deformation, compression load on the test sample is applied in several increments, and each increment is applied until the next consolidation is negligible. For each increment of load deformation versus time are recorded and time consolidation curve is drawn.

Oedometer (Consolidometer) Test

- Usually load is applied in increments of 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, 6.4, 12.8 and 25.6 kg/cm^2. and for each load increment deformation is recorded at time interval of 0.25, 0.5, 1.0, 2, 4, 8, 15, 30, 60, 120, 240, 480, and 1440 minutes.
- After completion of loading sequence, unloading is done in decrements to provide data for expansion during load release



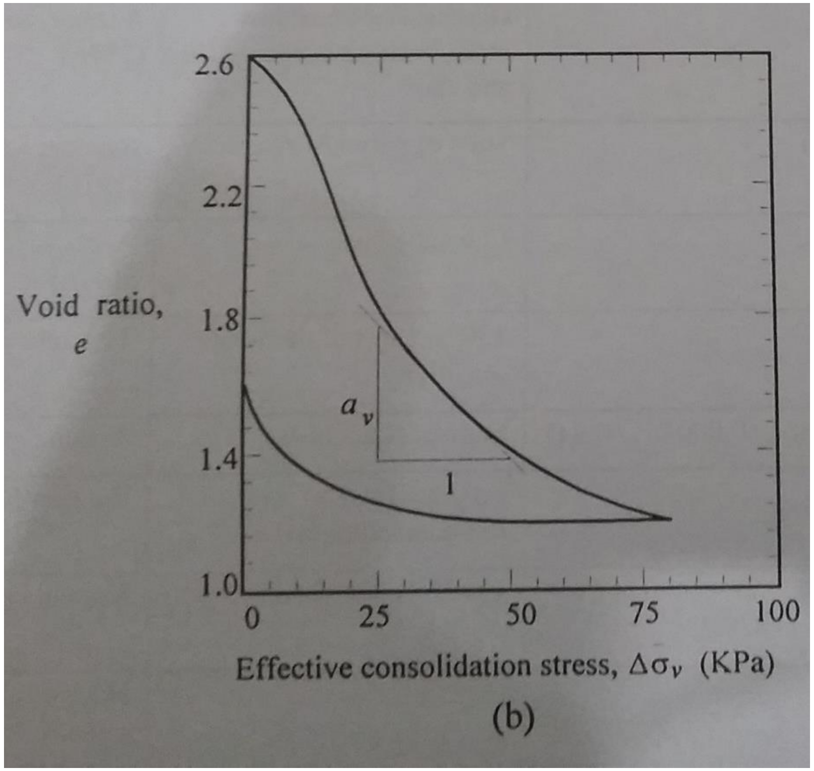
Schematic Sketch of Oedometer

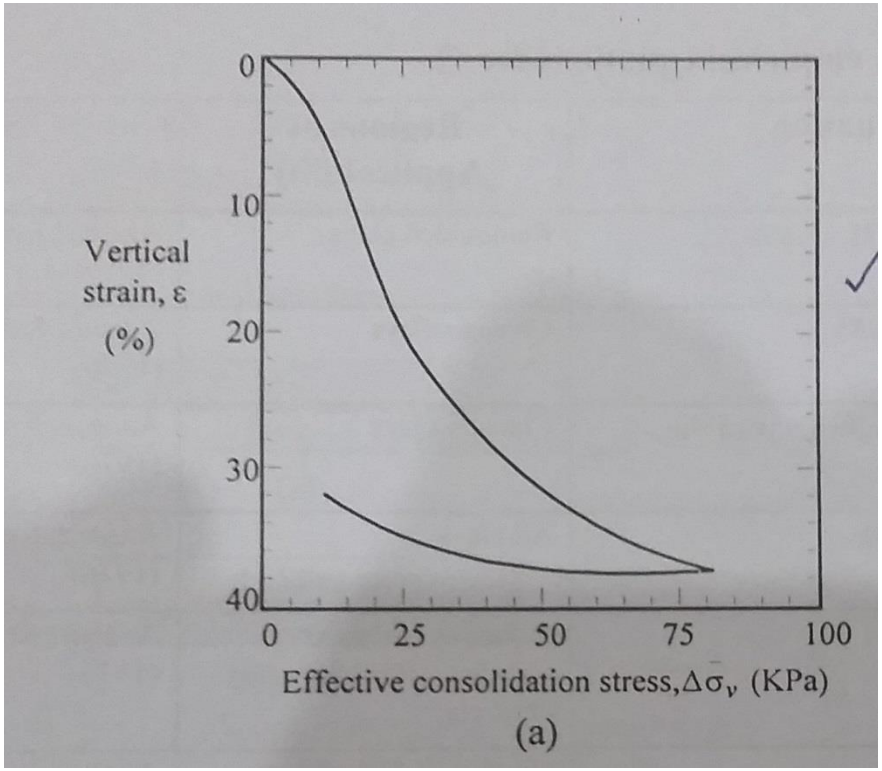
Oedometer (Consolidometer) Test

- There are different method to represent load deformation data. Two of them is shown in Following Figure.

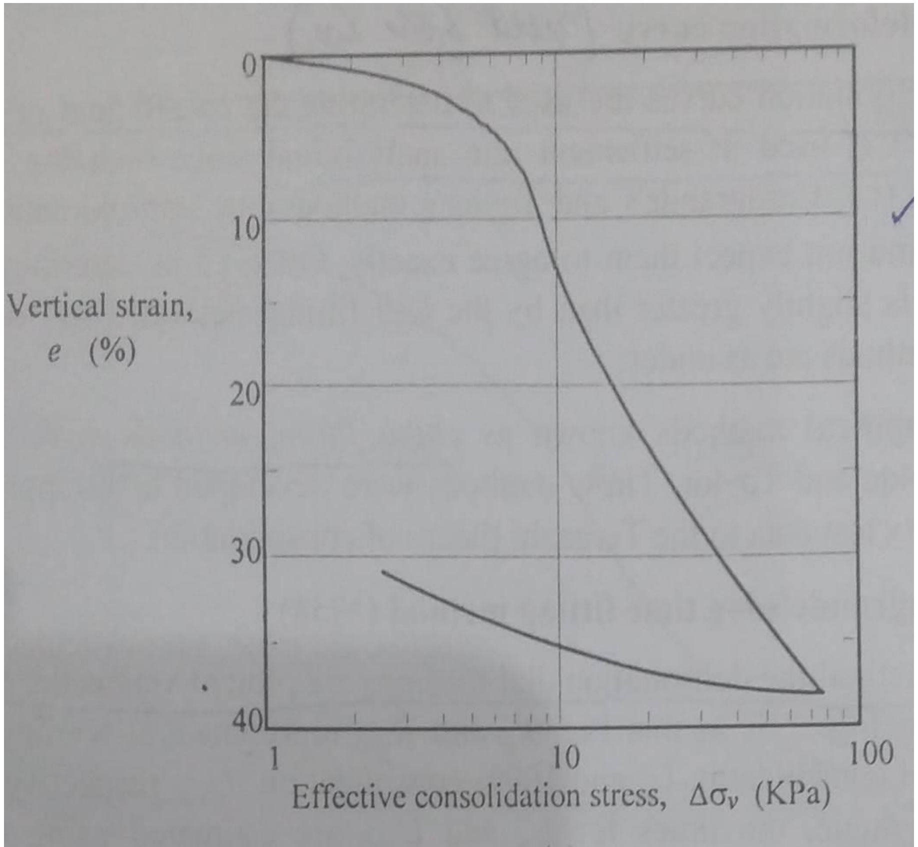
1. Vertical strain and effective consolidation stress
2. void ratio and effective consolidation stress

- Since this relationship is non linear, so more common way is to plot vertical strain or void ratio against "log of effective consolidation". In this way the nonlinear behavior of curve is reduced to approximately two straight line joined by a smooth transition curve.
- The stress at which the transition or break occur is the maximum vertical stress that this particular soil can sustained. This stress is very important in geotechnical engineering and is called pre consolidation pressure

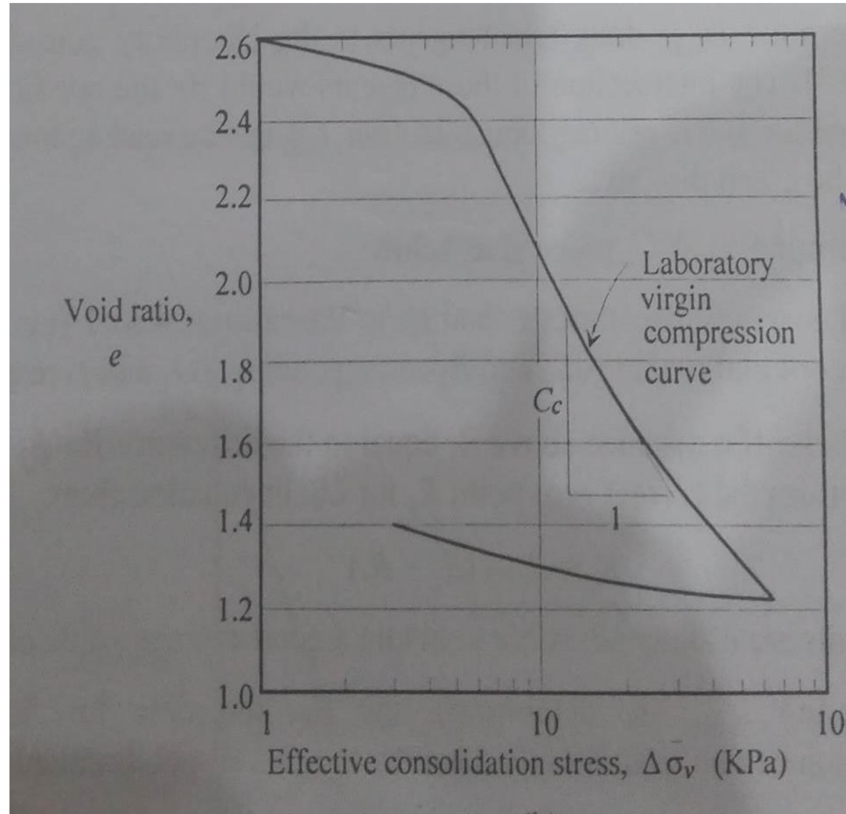




Two way present consolidation



(a)



(b)

Two way present consolidation (Using Log of Effective Stress)

Oedometer (Consolidometer) Test

- Slope of "void ratio" and "Log Effective consolidation stress" plot is known as compression index (C_c), which is used to compute the magnitude of total settlement
- Slope of "Void Ratio" and "Simple Effective Consolidation Stress" is called coefficient of compression and can be used to calculate total settlement

Time Deformation Curve

- Time deformation curve is used to determine the coefficient of consolidation (C_v) which is used in settlement rate analysis.
- There are two methods to determine (C_v).

1. Cassagrande log time fitting Method
2. Taylor's Square Root of Time Fitting Method

- **Cassagrande log time fitting Method**
- In this method the deformation dial readings are plotted versus the log of time as shown in following Figure. In this Figure R_0 and R_{100} represent dial readings for zero % degree of consolidation (U_0) and 100 % Consolidation (U_{100}) respectively. According to Cassagrande the time for U_0 and U_{100} are estimated using following procedure

1. To determine U_{100} , draw two tangent to the laboratory consolidation curve. The intersection of these tangents would fix the position of U_{100} and the time for 100 % primary consolidation , t_{100} can be read against this position from the graph directly.

Time Deformation Curve

- **Cassagrande log time fitting Method**

2. To determine R_0 and U_0.

I. Choose any two time t_1 and t_2 in the ratio of 4 to 1 ($t_2 = 4t_1$) and record dial gauge reading corresponding to t_1 and t_2.

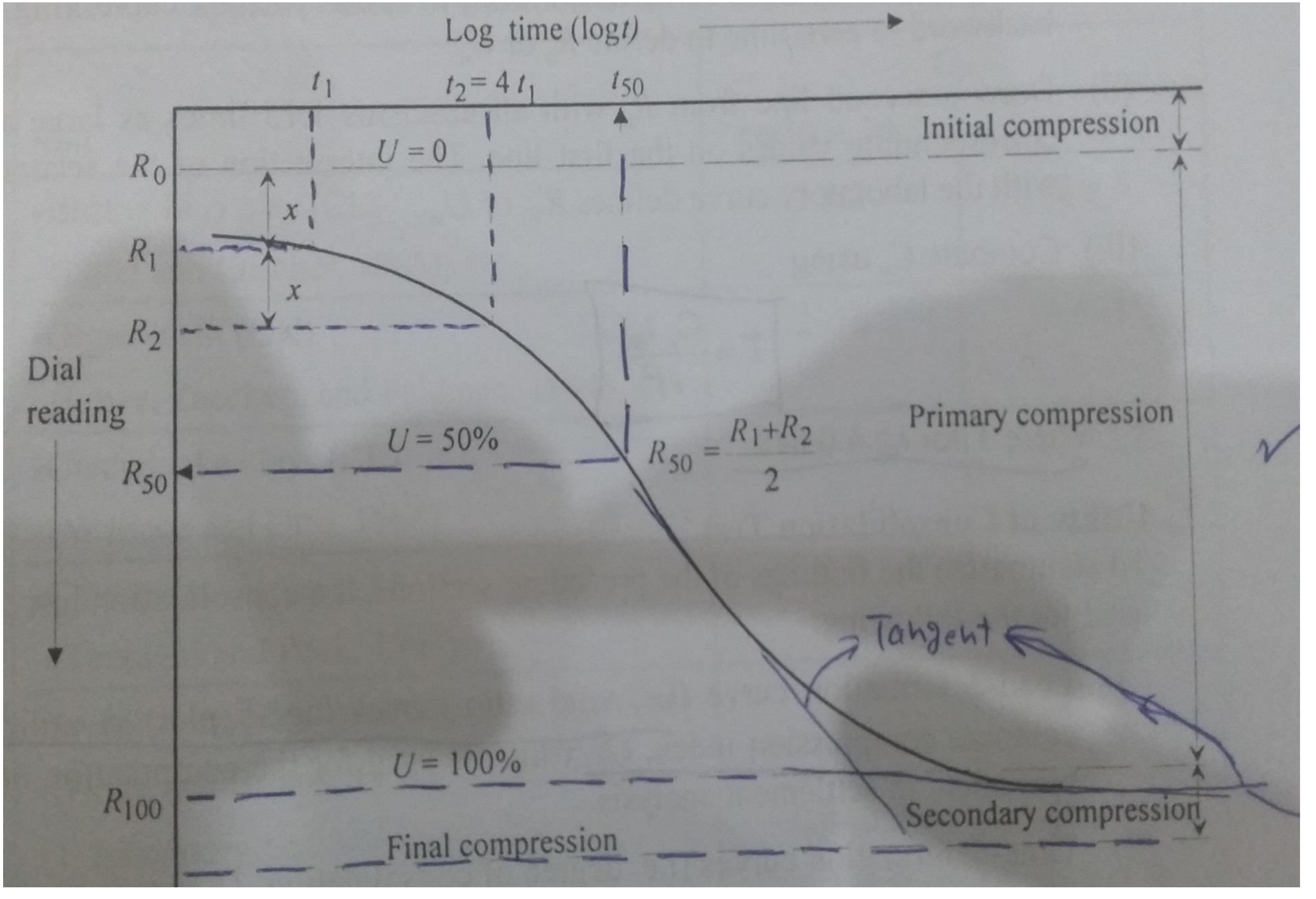
$$R_0 = R_1 - (R_2 - R_1)$$

II. Mark off a distance above R_1 equal to the difference of "R_2-R_1" let say (x). This defines the correct zero point R_0 for U_0. In equation form

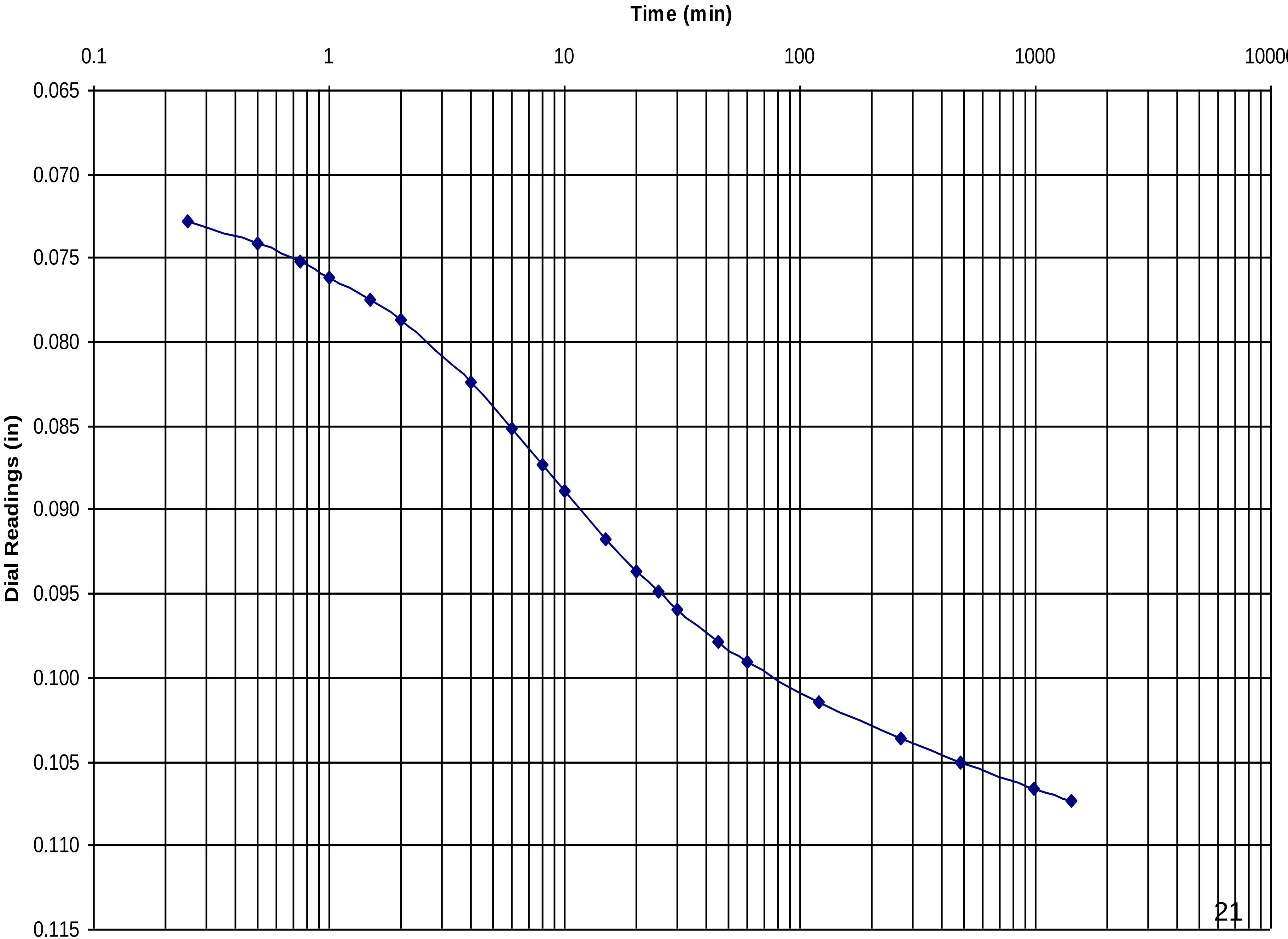
- Several trials are usually advisable to obtain a good value of R_0 and U_0.
- Once U0 and U100 are determined the t50 can easily be interpolated, so we can find (C_v) by using following equation

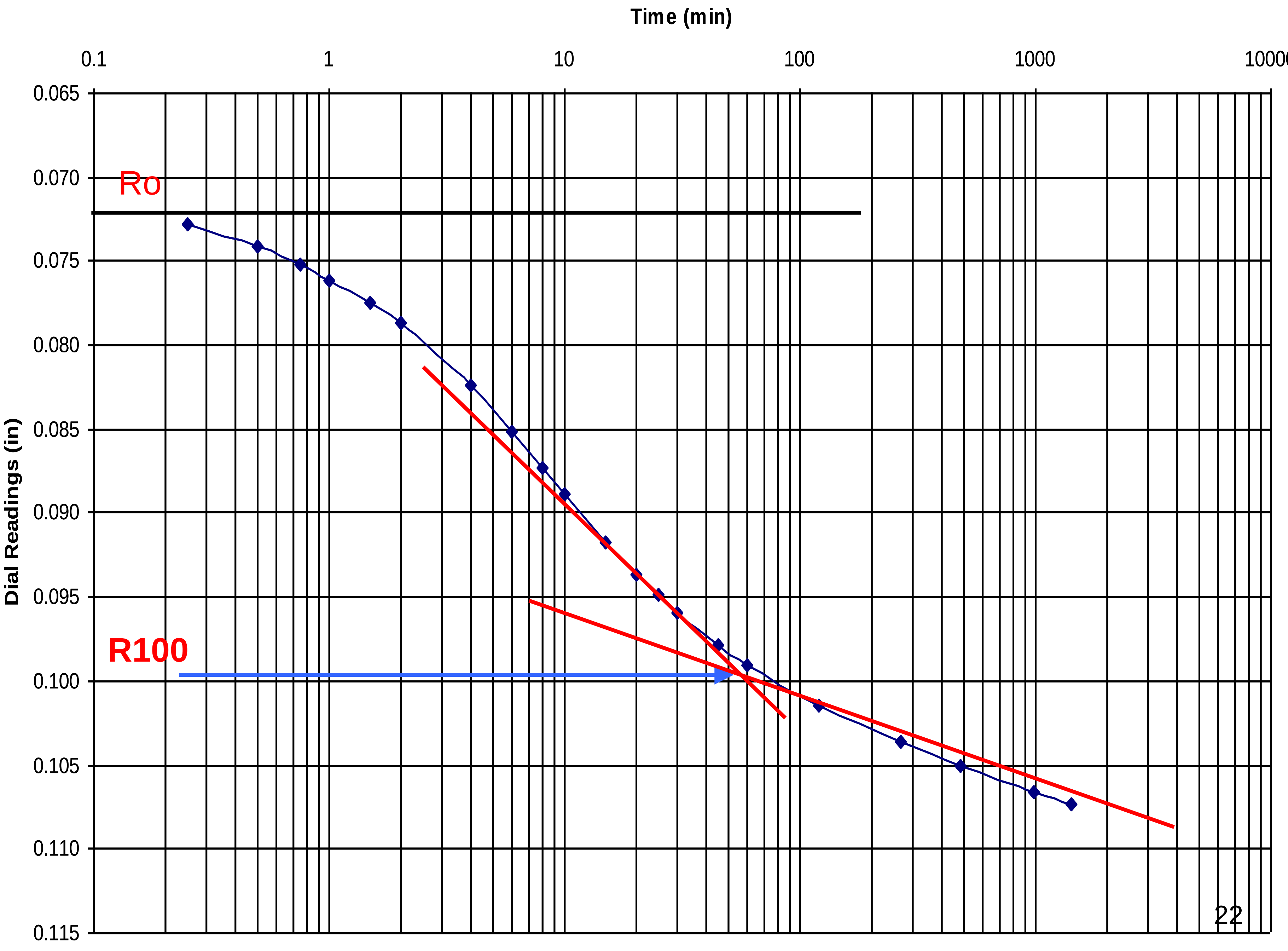
$$T = \frac{C_v . t_{50}}{H^2}$$

- T= time factor for $t_{50} = 0.197$

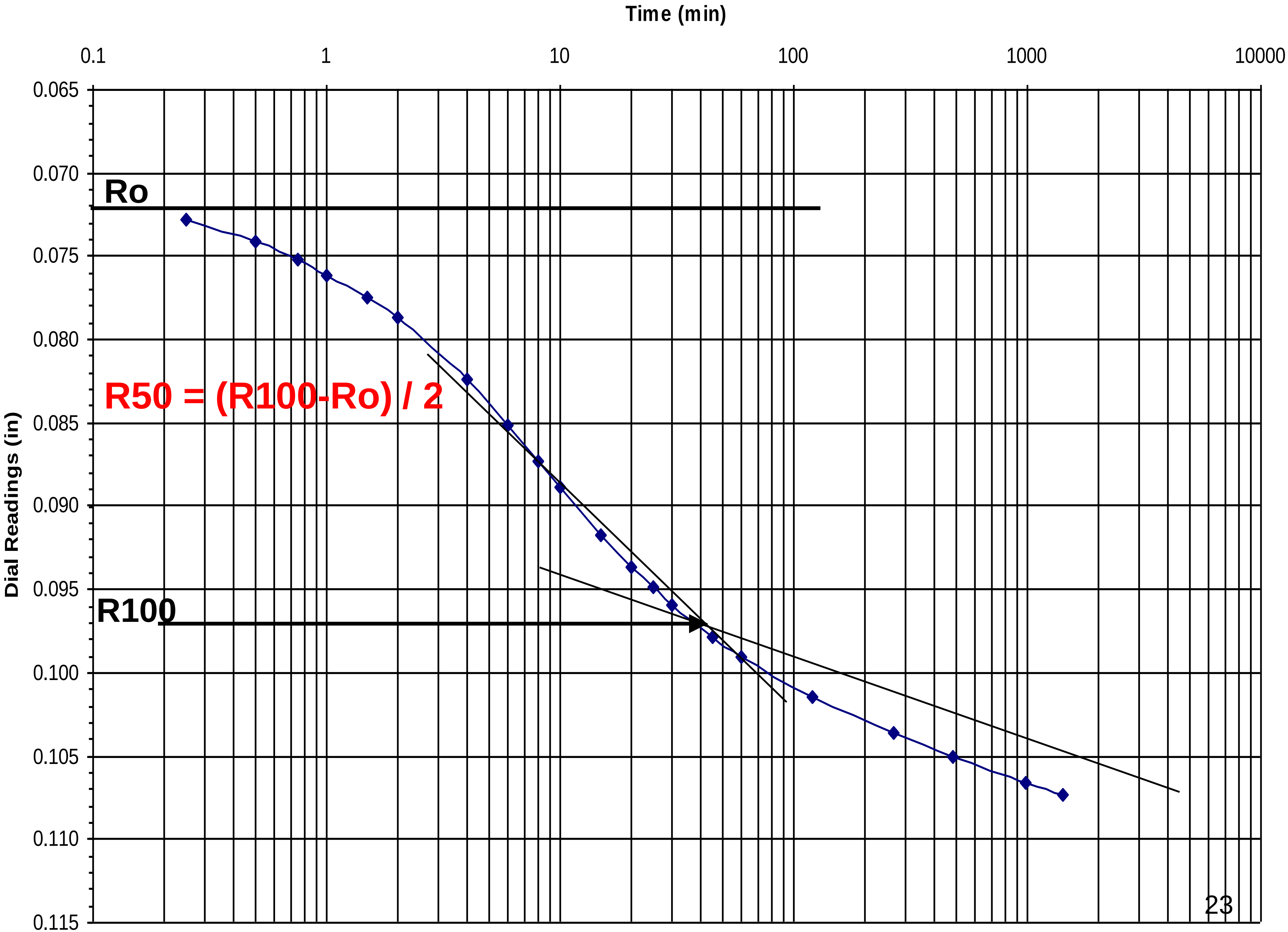


Determination of t_{50} by Cassagrande Method


Time (min)
0.1
1
10
100
1000
10000
Dial Readings (in)
0.065
0.070
0.075
0.080
0.085
0.090
0.095
0.100
0.105
0.110
0.115



Time (min)
0.1
1
10
100
1000
10000
Dial Readings (in)
0.065
0.070
0.075
0.080
0.085
0.090
0.095
0.100
0.105
0.110
0.115
Ro
R100



Time (min)
0.1
1
10
100
1000
10000
Dial Readings (in)
0.065
0.070
0.075
0.080
0.085
0.090
0.095
0.100
0.105
0.110
0.115
Ro
R50 = (R100-Ro) / 2
R100

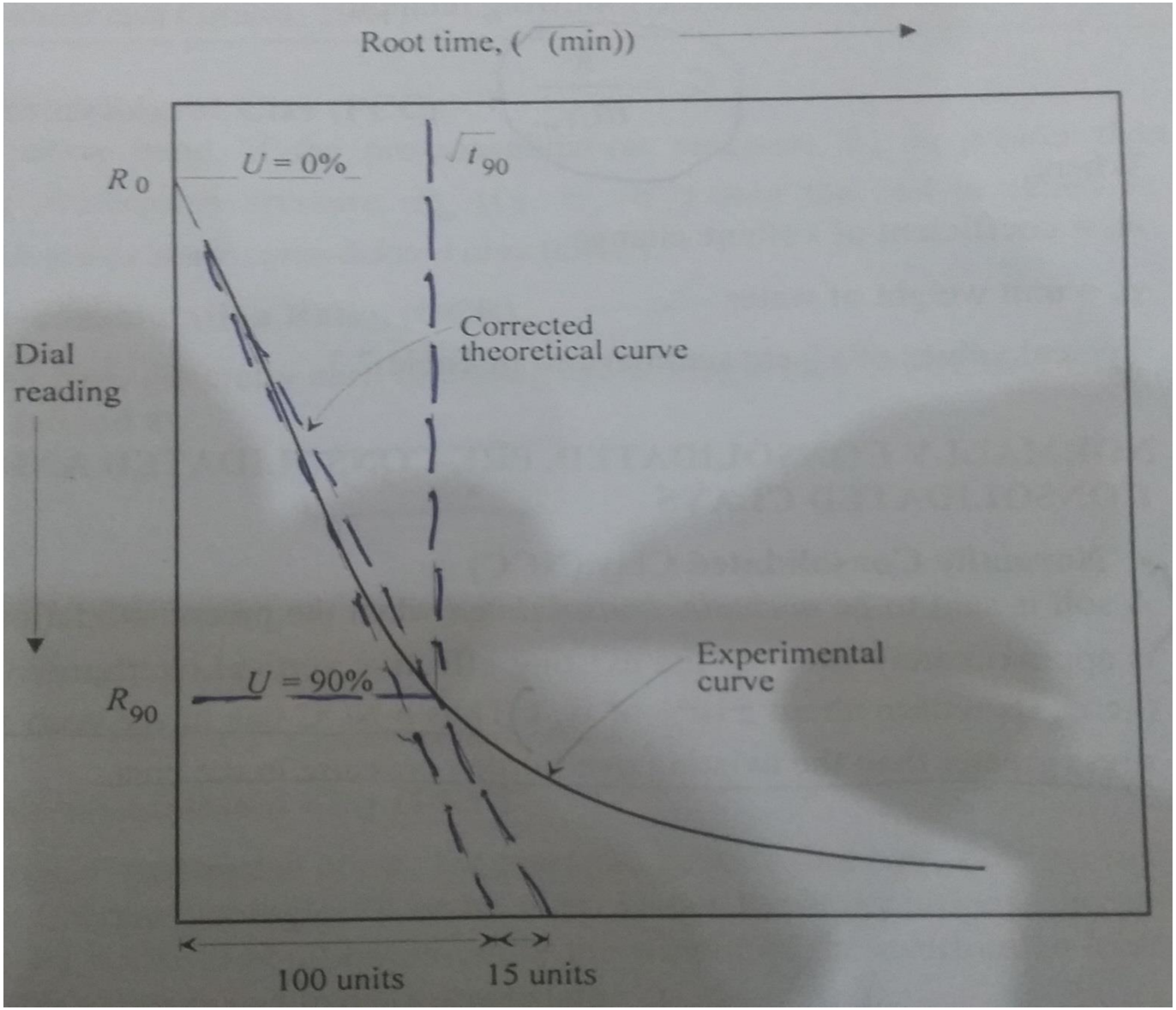
Time Deformation Curve

- **Taylor's Square Root of Time Fitting Method**
- Following Figure represents a curve of deformation dial reading plotted against Square root of time. Taylor observed that abscissa of the extension of the curve at 90% consolidation (U_{90}) was about 1.15 times the abscissa of the extension of the straight line and therefore this property of the plot helps in locating the position of U_{90} and t_{90}. To determine U_0 and R_0 here is the procedure

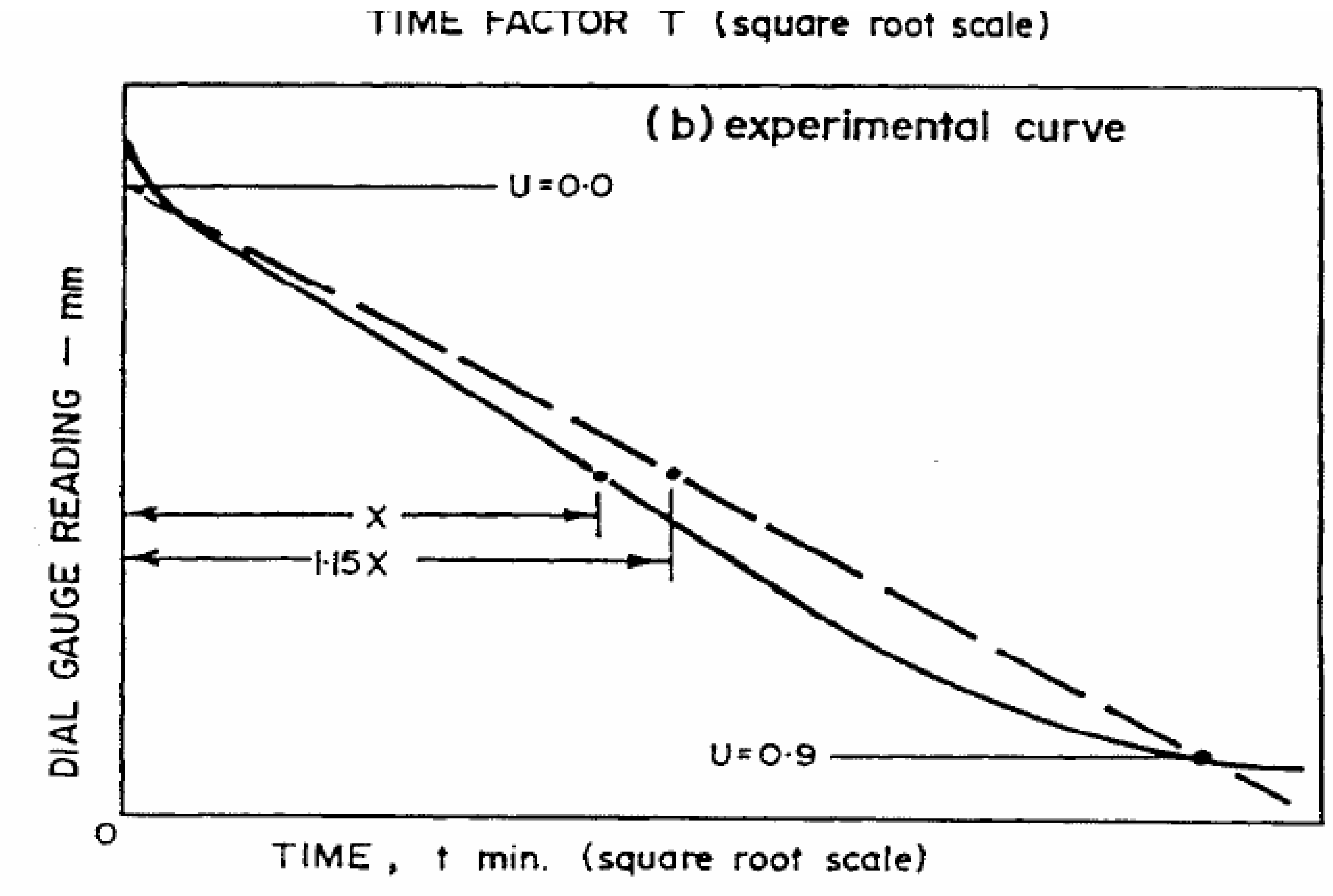
1. Project the straight line portion of the initial part of the curve backward to zero time to define R_0 and U_0.
2. Draw a second line from R_0 with all abscissas 1.15 times as larger as the corresponding values on the first line. The intersection of the second line with the laboratory curve defines R_{90} or U_{90}

$$T = \frac{C_v . t_{90}}{H^2}$$

- T = time factor t_{90}. = 0.848



Taylor's Square root Time Fitting Method


TIME FACTOR T (square root scale)
(b) experimental curve
U=0·0
X
1·15X
U=0·9
DIAL GAUGE READING — mm
O
TIME, t min. (square root scale)

Utility of Consolidation Test

- The consolidation test data is used for

1. Load deformation curve is utilized to compute compression index (C_c), which used for the computation of total settlement in settlement analysis.
2. Time deformation curve are used to compute coefficient of consolidation (C_v) which is used in rate of settlement analysis.
3. Consolidation test data can be used to calculate the coefficient of permeability

$$C_v = \frac{k}{m_v . \gamma_w}$$

- m_v= Coefficient of Volume Change
- C_v = Values given in the following table

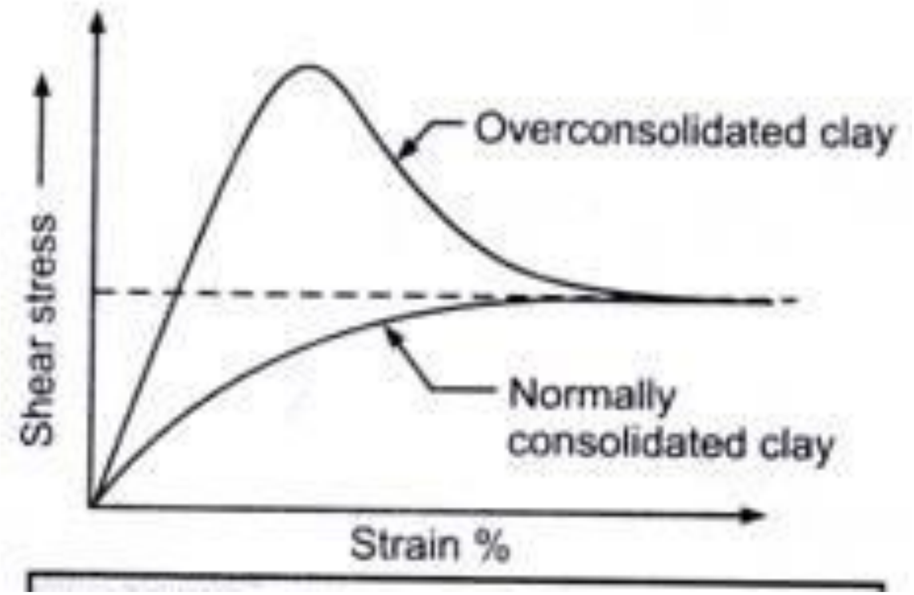
Table 7.3 Typical values of the coefficient of consolidation C_v

Soil	C_v	
	$cm^2/s \times 10^{-4}$	m^2/yr
•Boston blue clay (CL) (Ladd and Luscher, 1965)	40 ± 20	12 ± 6
•Organic silt (OH) (Lowe, Zaccheo, and Feldman, 1964)	2–10	0.6–3
•Glacial lake clays (CL) (Wallace and Otto, 1964)	6.5–8.7	2.0–2.7
•Chicago silty clay (CL) (Terzaghi and Peck, 1967)	8.5	2.7
•Swedish medium sensitive clays (CL–CH) (Holtz and Broms, 1972)		
1. laboratory	0.4–0.7	0.1–0.2
2 field	0.7–3.0	0.2–1.0
•San Francisco Bay Mud (CL)	2–4	0.6–1.2
•Mexico City clay (MH) (Leonards and Girault, 1961)	0.9–1.5	0.3–0.5

Pores)

Normally Consolidated Clay (NCC)

- A soil is said to be normally consolidated when the preconsolidation pressure ($\bar{\delta}_p$) (Preconsolidation pressure is the maximum effective vertical overburden stress that a particular soil sample has sustained in the past)is approximately equal to the existing effective overburden pressure ($\bar{\delta}_{vo}$), (i.e. $\bar{\delta}_{vo}$ is within $\pm$10% of $\bar{\delta}_p$).
- Thus a NCC has never been subjected to a stress greater than the existing overburden pressure in the past.



Over Consolidated Clay (OCC)

- On other hand, if the preconsolidation pressure ($\bar{\delta}_p$), is greater than the existing overburden pressure, (i.e.$\bar{\delta}_p > \bar{\delta}_{vo}$) then the soil is called as pre-consolidated or over-consolidated clay (OCC).

- **Over- Consolidated Ratio (OCR)**
- OCR is a tool, generally used to distinguish amongst NCC, OCC and UCC soil.
- This is defined as

$$OCR = \frac{\bar{\delta}_p}{\bar{\delta}_{vo}}$$

- For:
- NCC…………………….OCR = 1
- OCC…………………….OCR > 1
- UCC…………………….OCR < 1

Under- Consolidated Clay (UCC)

- Under-consolidation can occur, for example in soils that have only recently been deposited, either geologically or by man. Under these conditions, the soil layer has not yet come to equilibrium under the weight of the overburden load that is the pore pressure is in a hydro excess state.
- A soil could be considered under consolidated immediately after a new load is applied but before the excess pore water pressure has had time to dissipate.

Comparison of NCC and OCC

Description of Parameter	NCC	OCC
Natural Moisture content, w_n	High, usually close to liquid limit	Relatively low, usually less than plastic limit
Density, γ	Relatively low	Usually high compared to NCC
Liquidity index	0.6 – 1 and over	0 – 0.6
SPT-resistance	Low with consistency between very soft and firm	High, with consistency stiff to hard
Compressibility	Under a given intensity of loading, settlement is comparatively higher	Settlement is relatively small for the same intensity of loading
Unconfined compression strength, q_u	Very low to low	Medium to high

Terzaghi One Dimensional Consolidation Theory

- **Assumptions**

1. The soil is assumed to be homogeneous.
2. Soil is fully saturated (i.e. all voids are full of water with no air)
3. Water in voids is assumed to be incompressible so that the change in volume is due to change in volume of voids
4. The sample is laterally confined, only vertical settlement and vertical drainage are allowed.
5. The coefficient of permeability is considered to be constant throughout the soil.
6. Darcy law of permeability is valid

Terzaghi One Dimensional Consolidation Theory

- Terzaghi presented the following Fourier series equation to calculate Consolidation

$$U = \left(\bar{\delta}_2 - \bar{\delta}_1\right) \sum_{n=0}^{\infty} f_1(Z)\, f_2(T)$$

- Where (Z) and (T) are dimensionless parameters.
- Z is a geometry parameter, and it is equal to = Z/H
- T is called a time factor and is given by

$$T = C_v \cdot \frac{t}{H^2}$$

- Where
- t = Time for certain degree of consolidation
- H = Length of drainage path, for double drainage path it is “2H”.

Terzaghi One Dimensional Consolidation Theory

- The progress of consolidation after some time "t" at any depth "Z" in the consolidation layer is called "compression ratio" (U_z) or % of consolidation and is given by

$$U_z = \frac{e_1 - e}{e_1 - e_2} = \frac{\bar{\delta} - \bar{\delta}_1}{\bar{\delta}_2 - \bar{\delta}_1} = \frac{u_i - u}{u_i} = 1 - \frac{u}{u_i}$$

- So previous equation is reduced to

$$U_z = 1 - \sum_{n=0}^{\infty} f_1(Z)\, f_2(T)$$

THANK YOU!