Lecture-6

Soil consolidation

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CONSOLIDATION OF SOIL

When a soil mass is subjected to a compressive force there is a decrease in volume of soil mass.

The reduction in volume of a saturated soil mass due to expulsion of water from the voids under the action of steady static pressure is called consolidation.

Types of Consolidation:

1. **Primary consolidation**
2. **Secondary consolidation**

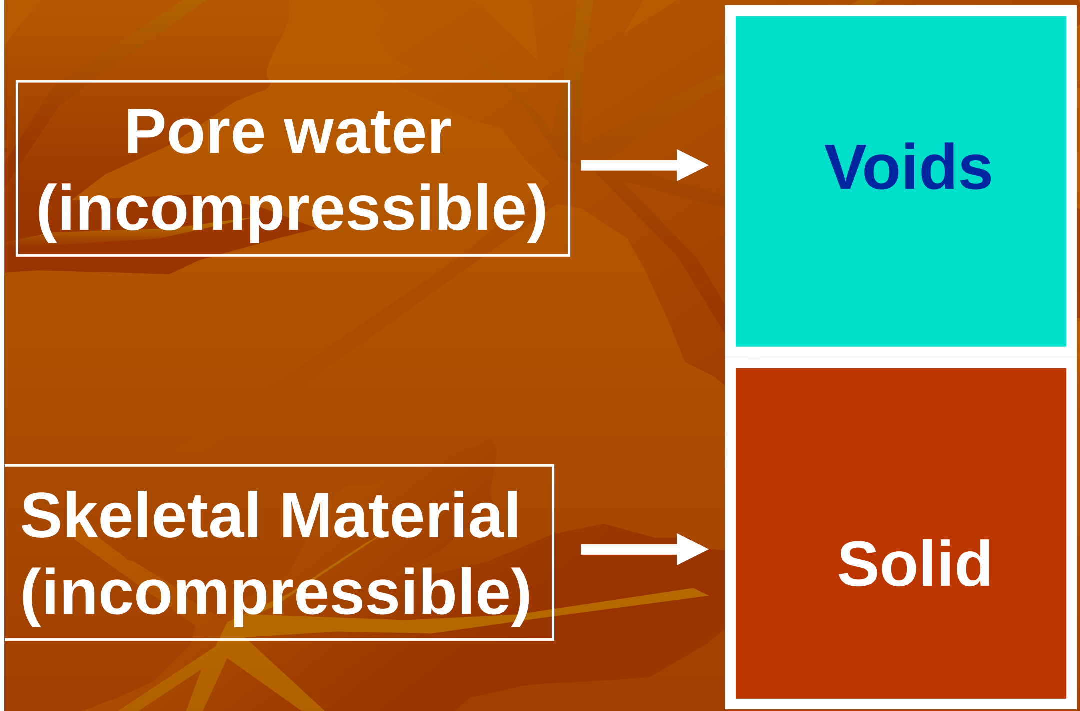
1. Primary Consolidation:

It is the reduction in volume due to expulsion of water from the voids. Expulsion of water from the voids depends on permeability of soil and it is therefore time dependent.

2. Secondary Consolidation:

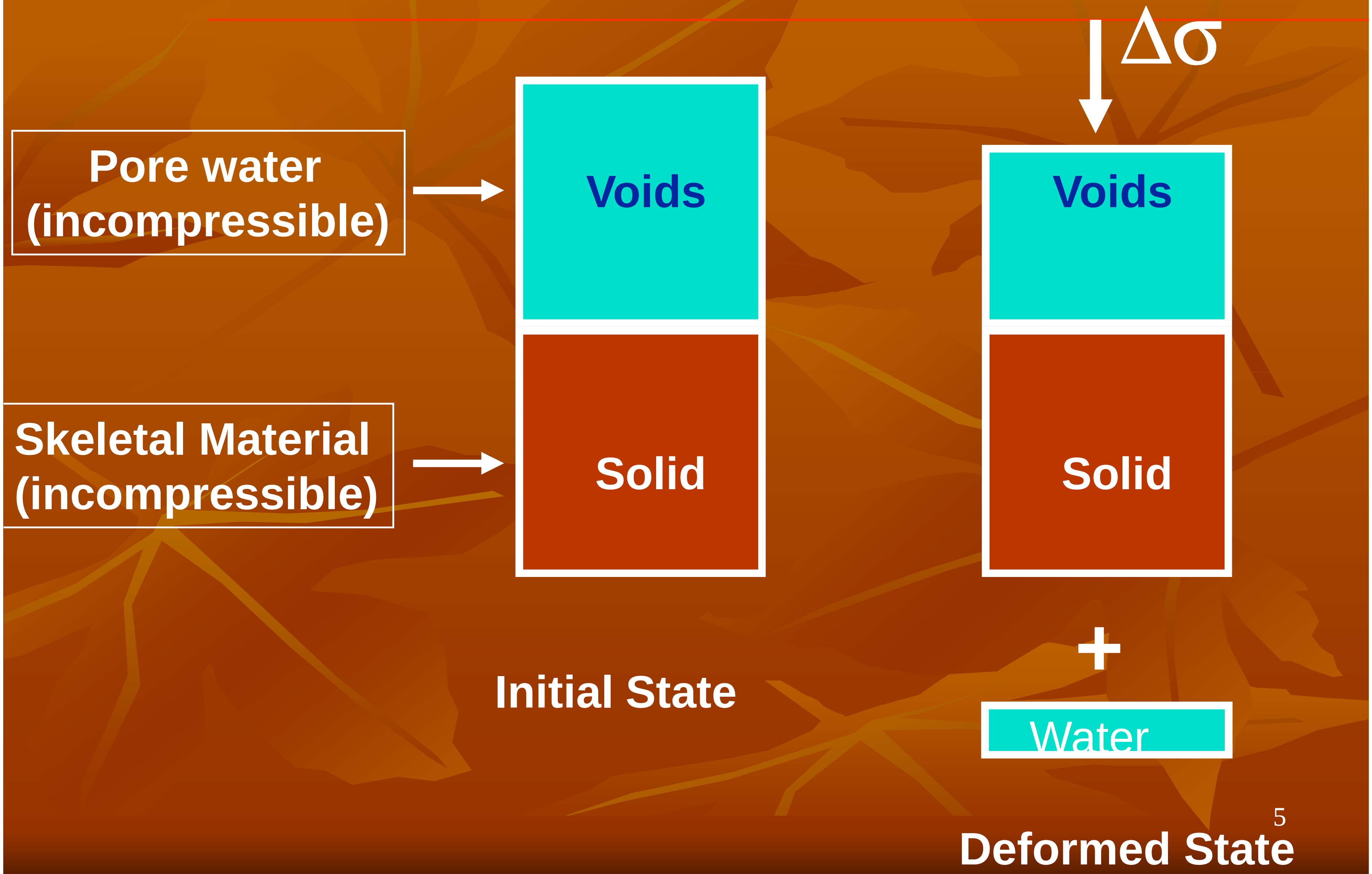
When all the water is squeezed out of the voids and primary consolidation is completed, further reduction in volume of soil is called secondary consolidation. It may be due to plastic deformation of the soil particles or some other reasons. The value is however very small and commonly neglected.

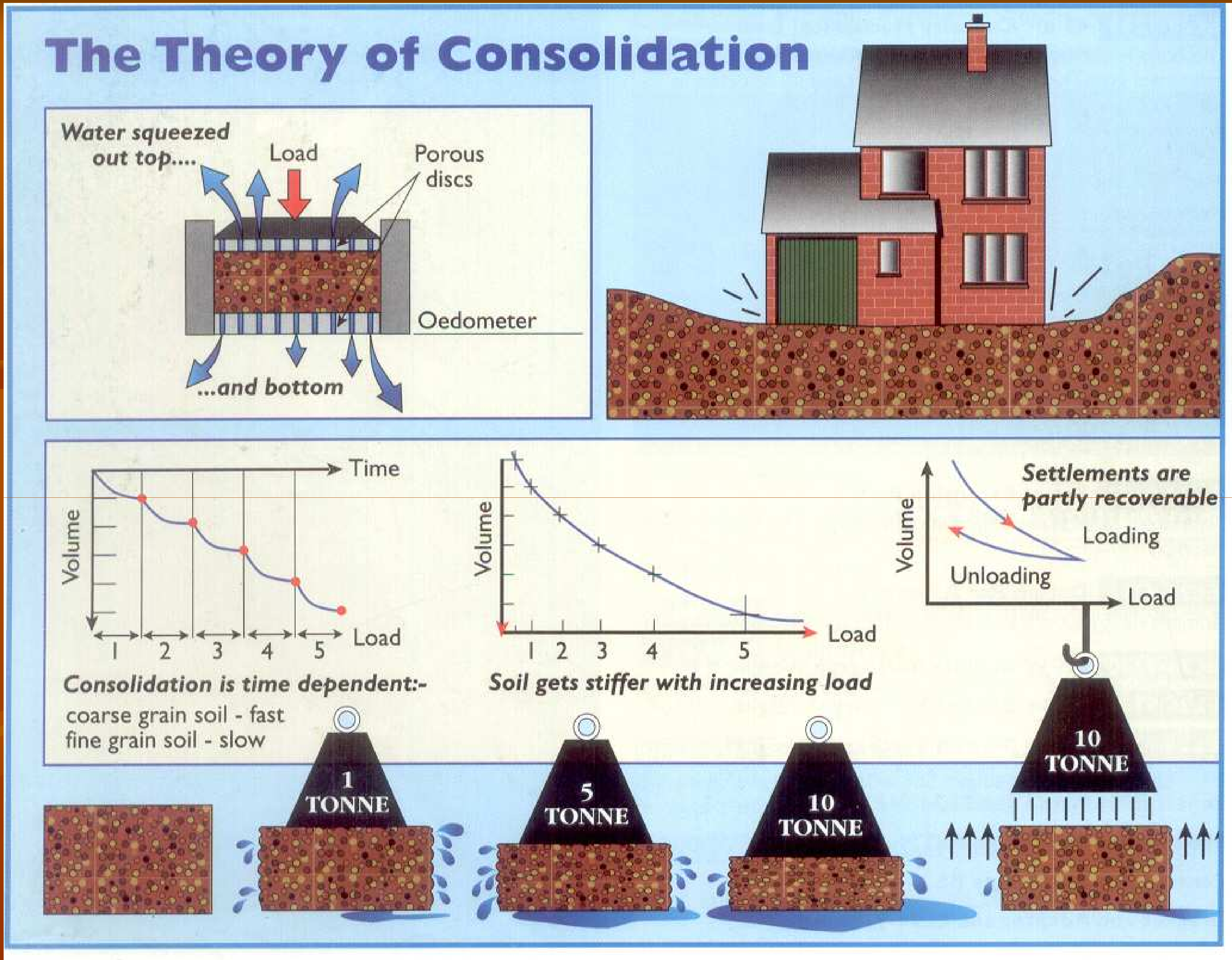
The consolidation process



Initial State

The consolidation process




The Theory of Consolidation
Water squeezed out top....
Load
Porous discs
Oedometer
...and bottom
Time
Volume
1 2 3 4 5
Load
Consolidation is time dependent:-
coarse grain soil - fast
fine grain soil - slow
Volume
1 2 3 4 5
Load
Soil gets stiffer with increasing load
Settlements are partly recoverable
Volume
Loading
Unloading
Load
10 TONNE
1 TONNE
5 TONNE
10 TONNE

The consolidation process

Deformation of saturated soil occurs by reduction of pore space & the squeezing out of pore water. The water can only escape through the pores which for fine-grained soils are very small

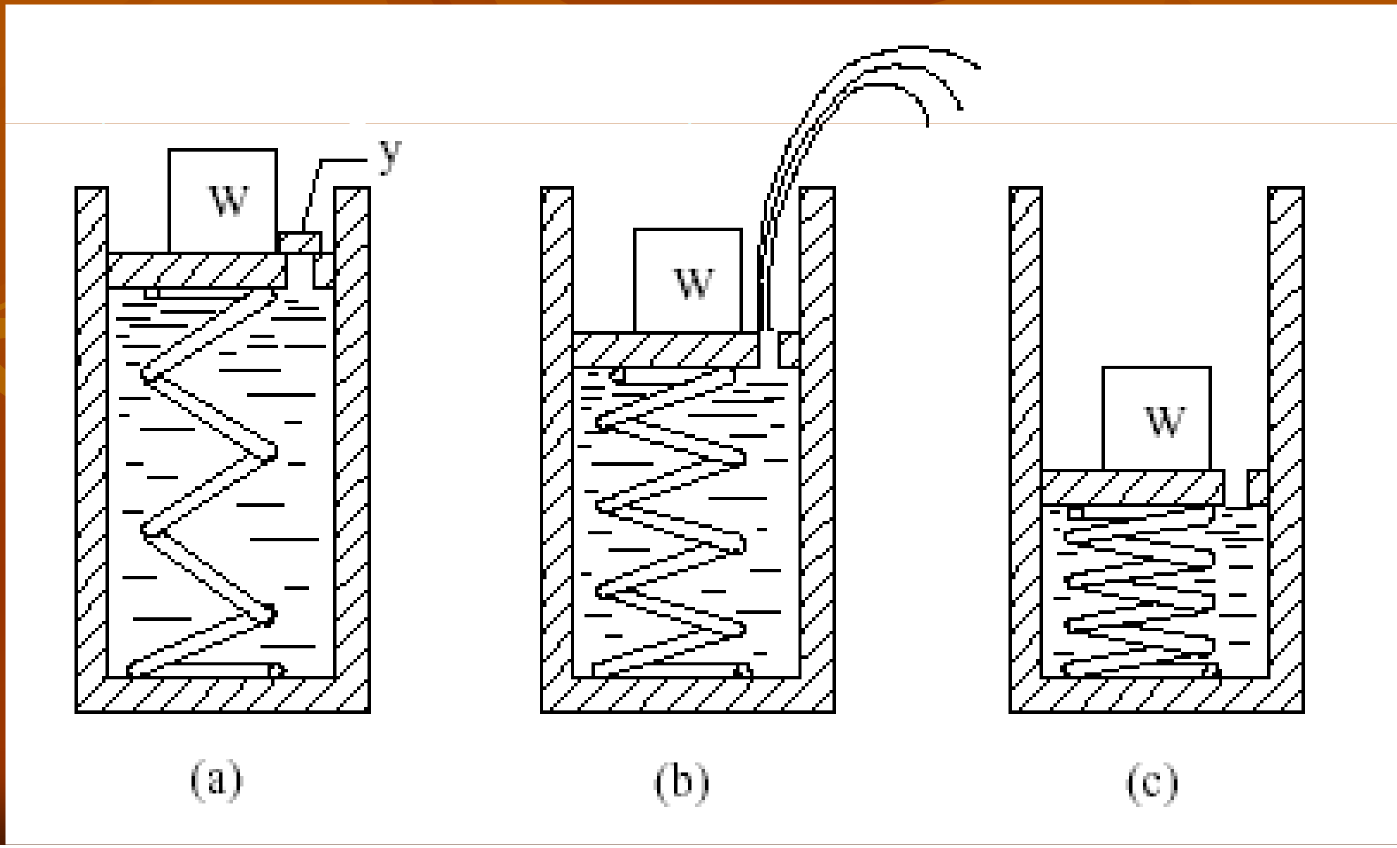
SPRING ANALOGY FOR PRIMARY CONSOLIDAITON

When a pressure '$\Delta\sigma$' is applied to a saturated soil mass, the solid particles and water in the voids share the pressure.

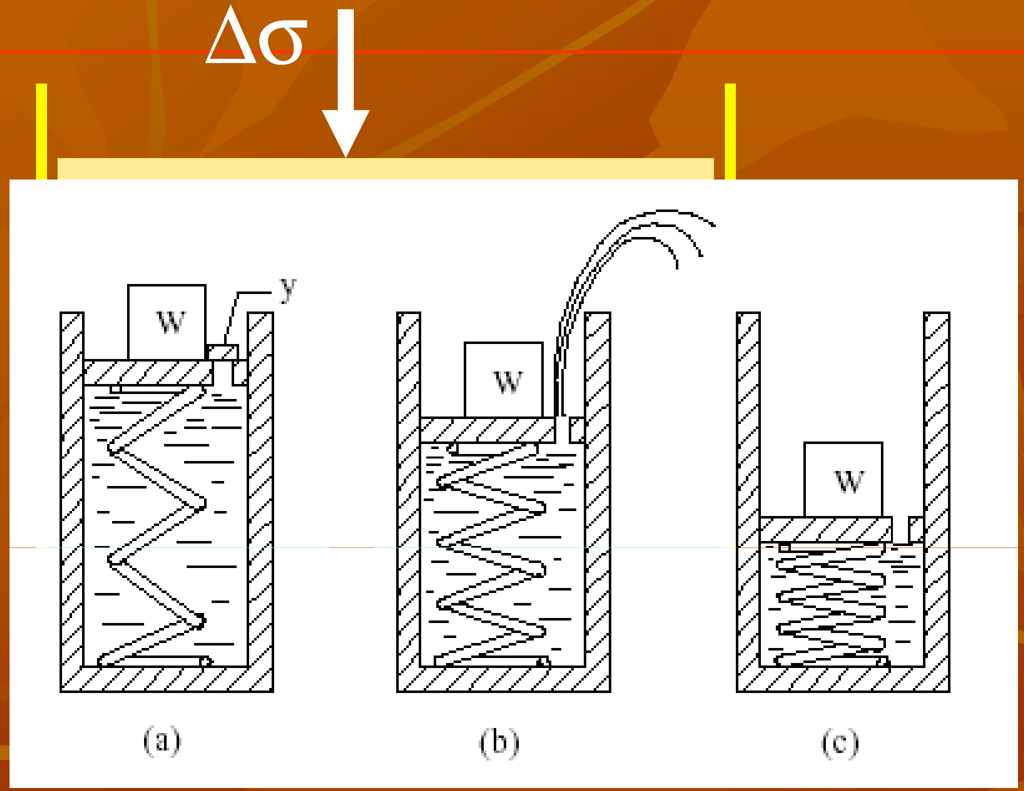
$$\Delta\sigma = \Delta\sigma' + U$$

The consolidation process

Deformation of saturated soil occurs by reduction of pore space & the squeezing out of pore water. The water can only escape through the pores which for fine-grained soils are very small

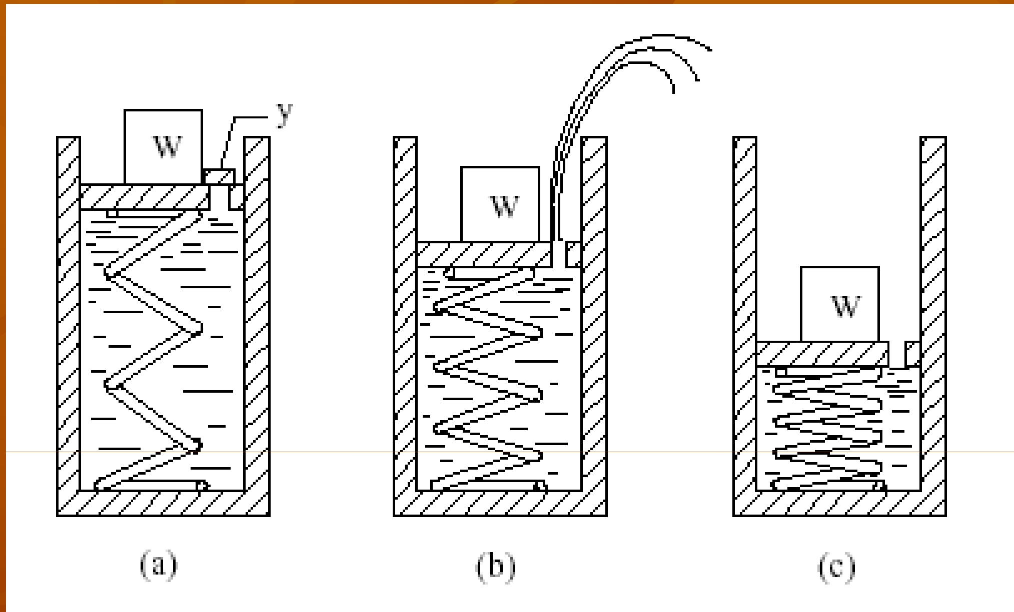


The consolidation process



Instantaneously no water can flow, and hence there can be no change in volume.

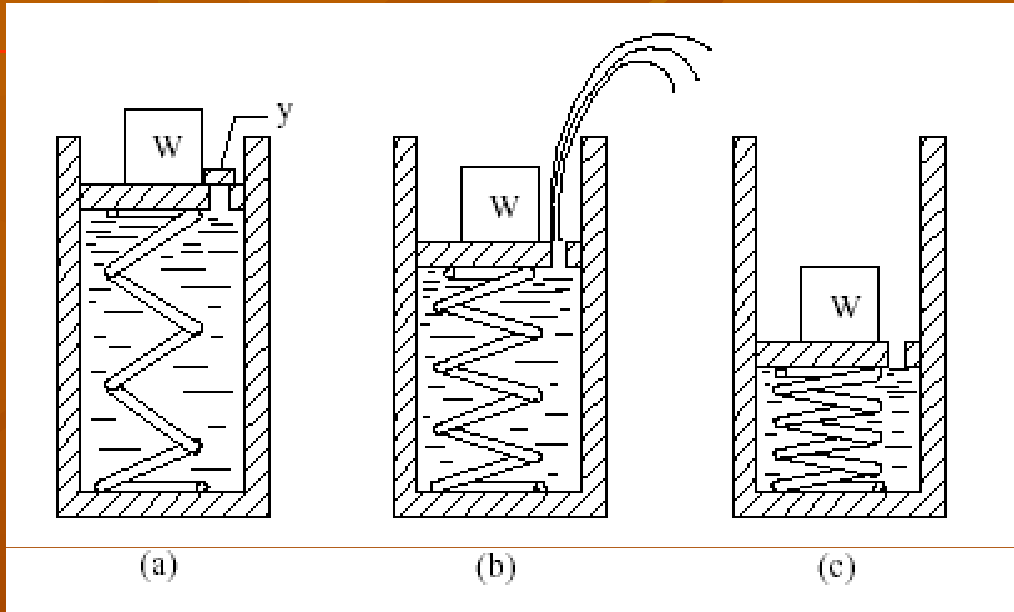
The consolidation process



Instantaneously no water can flow, and hence there can be no change in volume.

For 1-D conditions this means

The consolidation process



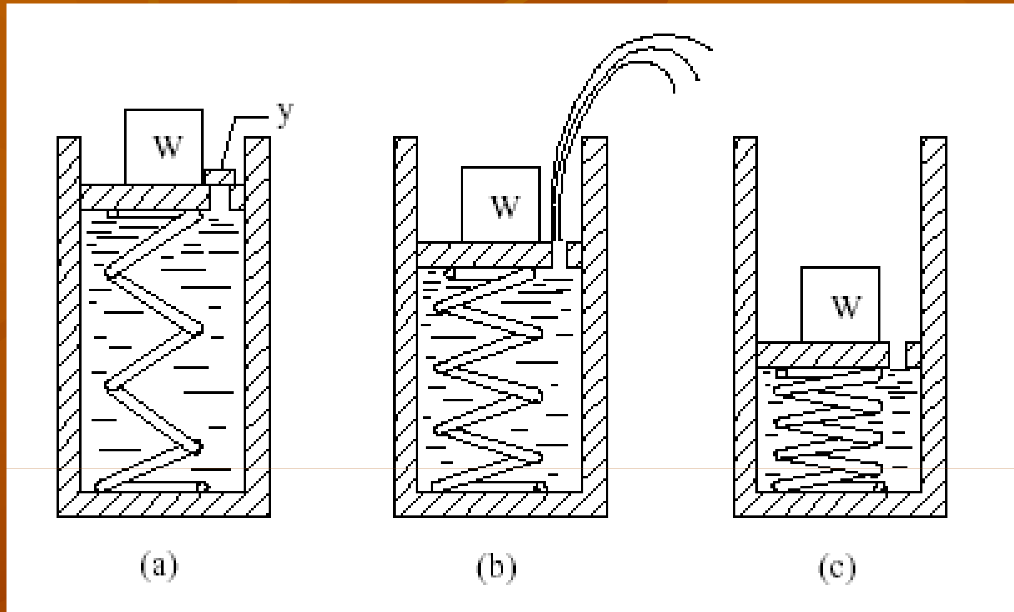
Instantaneously no water can flow, and hence there can be no change in volume.

For 1-D conditions this means

$$De_{zz} = De_{v} = \frac{-\ \Delta e}{1 + e} = \frac{C \ \ \log(\sigma'_F / \sigma'_I)}{1 + e} = 0 \qquad (1)$$

and hence Ds´ = 0 instantaneously

The consolidation process



From the principle of effective stress we have

$$\Delta\sigma = \Delta\sigma' + \Delta u \qquad (2)$$

and thus instantaneously we must have

$$\Delta\sigma = \Delta u$$

- **$\Delta\sigma'$= The pressure shared by soil particles (Effective stress)**
- **U = Pressure shared by water (Hydrostatic pressure/Pore water pressure)**
- **Just after application of pressure the entire pressure is carried by water.**
- **Pressure developed in water, known as excess hydrostatic pressure (U) is equal to the applied pressure.**
- **Pressure taken by the solid particles (effective stress = $\Delta\sigma'$) is zero**

$$\Delta\sigma = U \text{ ... at time } t = 0$$

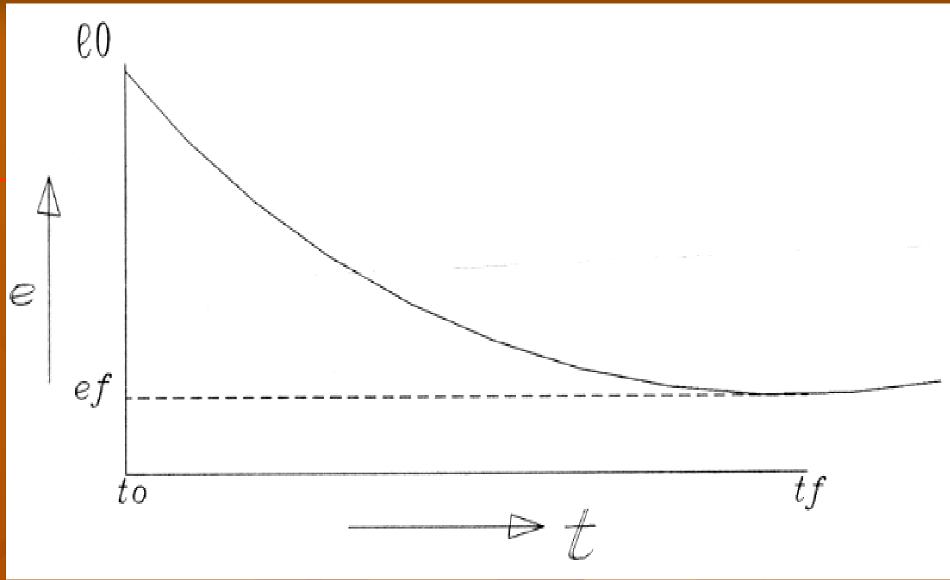
- **The excess hydrostatic pressure slowly decreases as water escapes from the voids; the applied pressure is transferred from the water to the solid particles.**

- $\Delta\sigma = U + \Delta\sigma'$ **... at any time t**

- **Eventually all the pressure is transferred to the soil particles as an effective stress, and the excess water Pressure becomes zero. Thus**

- $\Delta\sigma = \Delta\sigma'$ **... at time t = tf**

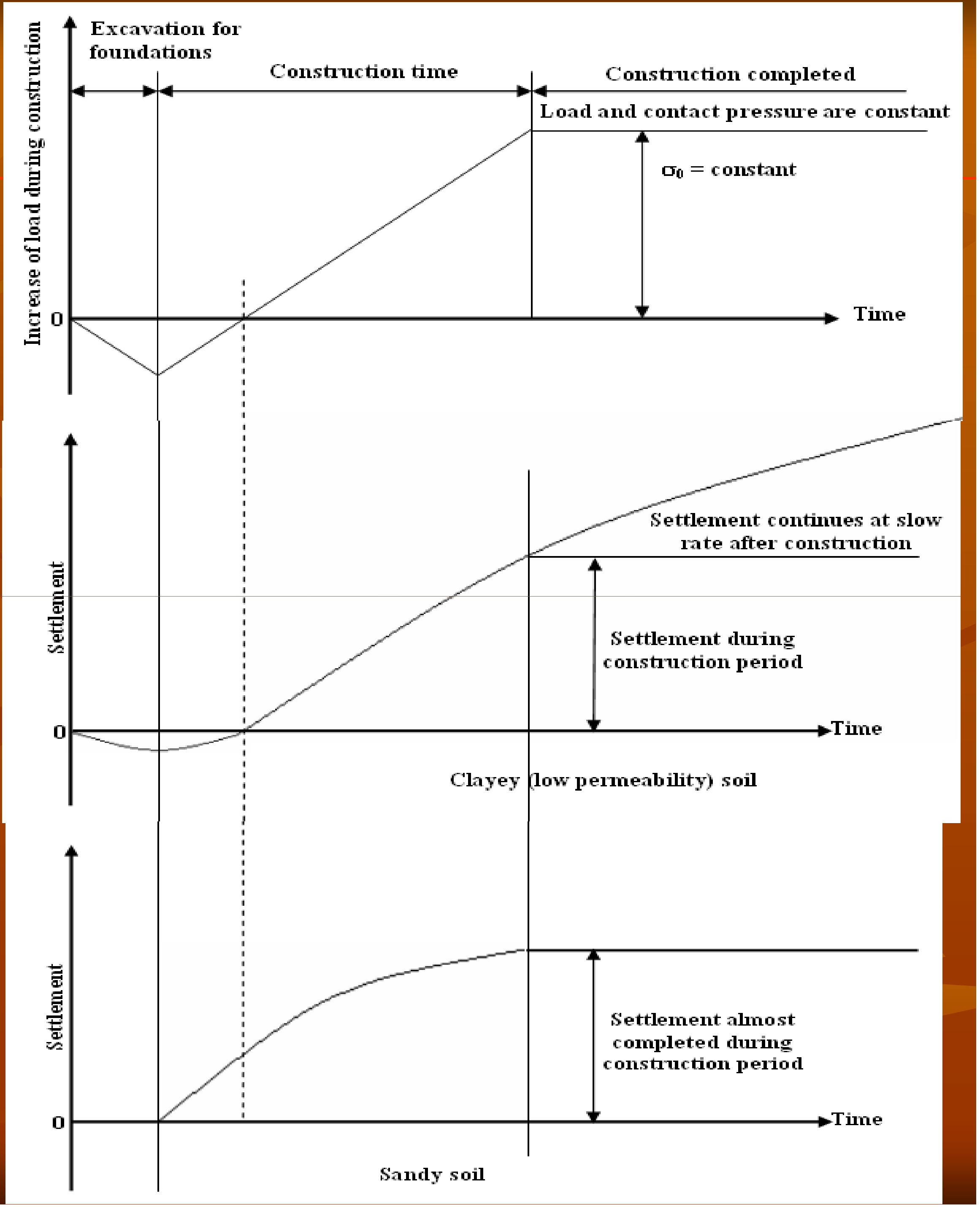
- **As the effective stress increases due to dissipation of excess hydrostatic pressure, the volume of the soil decreases. The decrease in volume is generally expressed, as change is void ratio.**



- **Decrease in volume of sandy soil (coarse grained) under the loads of buildings and structures occurs as soon as these loads are applied due to the greater permeability. The resulting settlement is called immediate settlement, a major portion of which is completed during the construction period.**

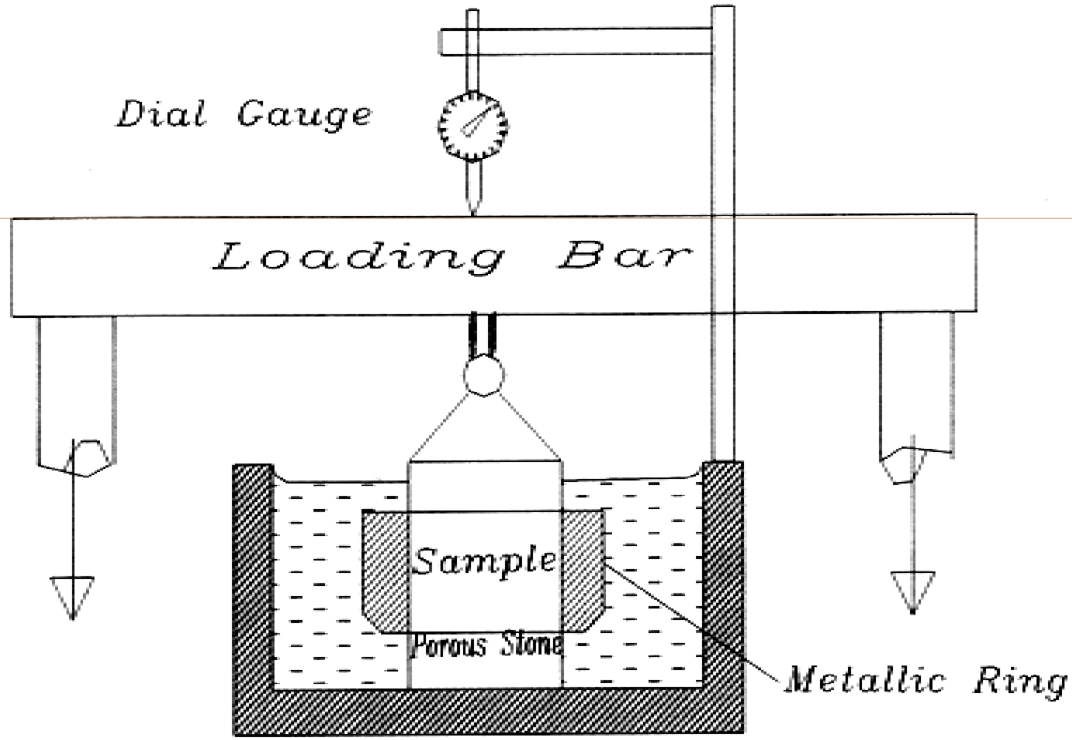
- **Buildings founded on cohesive (fine-grained) soils due to low permeability settles for a long time at a continuously decreasing rate before becoming stationary. This long-term compression of cohesive soils under a constant steady load is called consolidation settlement.**

Load ~ settlement behaviour of fine and coarse grained soils in terms construction stages and corresponding settlement



Consolidation Test

Consolidation Test:-



Consolidation or Oedometer test

- Apparatus is shown in the last figure.
- Soil sample confined in a ring is placed in the consolidation cell between top and bottom porous stones.
- Internal diameter of the ring (or diameter of sample) ranges from 50 mm to 100 mm.
- Thickness of sample should be as small as possible to reduce side friction, a minimum thickness of 20 mm is usually used.
- Cell is connected to a water reservoir so as to keep the sample fully saturated through out the test.
- Dial gauge is used to measure the change in thickness as consolidation takes place.
- Loads are applied to the sample in equal increments ranging from a pressure of 0.5 kg/cm^2 to 8 kg/cm^2.
- Each load increment is applied for 24 hours, and the compression of the sample is measured. The readings of dial gauge are taken at intervals of 0.25, 0.5, 1, 2, 4, 8, 15, 30, 60 minutes 2, 4 8 and 24 hours.
- After 24 hours next load increment is applied, the usual range of load increments are 0.5, 1,2,4,8 kg/cm^2.

- After consolidation under the final load increment, the load is reduced to one- fourth of the final load and allowed to stand for 24 hours. The sample takes water and swells. The load is finally reduced to the initial setting load and kept for 24 hours and the final dial gauge reading is taken to rebound.
- Immediately after complete unloading, the ring with the sample is taken out. The excess water is dried with a blotting paper. The weight of the ring and sample is taken. The sample is dried in an oven for 24 hours and final moisture content is determined.

Important parameters determined from the consolidation test are

1. Determination of Void Ratio:

Determination of void ratio at various load increments is required to plot curve between the void ratio and effective stress

$$Vs = HsA$$

$$Hs = \frac{Vs}{A}$$

$$Hs = \frac{Ws}{G\gamma wA}$$

$$G = \frac{\gamma s}{\gamma w} = \frac{Ws}{Vs\gamma w}$$

$$Vs = \frac{Ws}{G\gamma w}$$

Hs = Height of solids
Vs = Volume of solids
Ws = Dry wt. Of sample (At the end of test by oven drying)
G = Specific gravity of solids
A = X-sectional area of specimen
γ_w = Unit weight of water

Now

$$e = \frac{Vv}{Vs} = \frac{V - Vs}{Vs}$$

V = H x A **H = total height of sample at any time.**

$$e = \frac{HA - Hs\ \ A}{Hs\ \ A} = \frac{A(H - Hs)}{A\ \ Hs}$$

$$e = \frac{H - Hs}{Hs}$$

Initial void ratio at the start of the test

$$eo = \frac{Ho - Hs}{Hs}$$

Ho = **Initial height of the sample**

H = Ho - ΔH

Where ΔH = Change in thickness between any two loading stages, and is determined from the difference in readings of the dial gauge.

Determination of m_v:

m_v = Coefficient of volume decrease or coefficient of compressibility

$$m_v = -\frac{\Delta e}{\Delta p(1+e_1)}$$

Δe = Change in void ratio

Δp = Change in applied pressure

e_I = Initial void ratio

It is used to find total settlement

Compressibility (a_v):

$$av = -\frac{\Delta e}{\Delta p}$$

- **It is the rate of change of void ratio with corresponding change in pressure.**
- **- Ve sign indicate decrease in void ratio with increase of pressure.**

Co-efficient of Consolidation C_v:

$$Cv = \frac{\tau v \ H^2}{t} =$$ ***cm² / sec, ft² / year***

It is used to measure rate of settlement

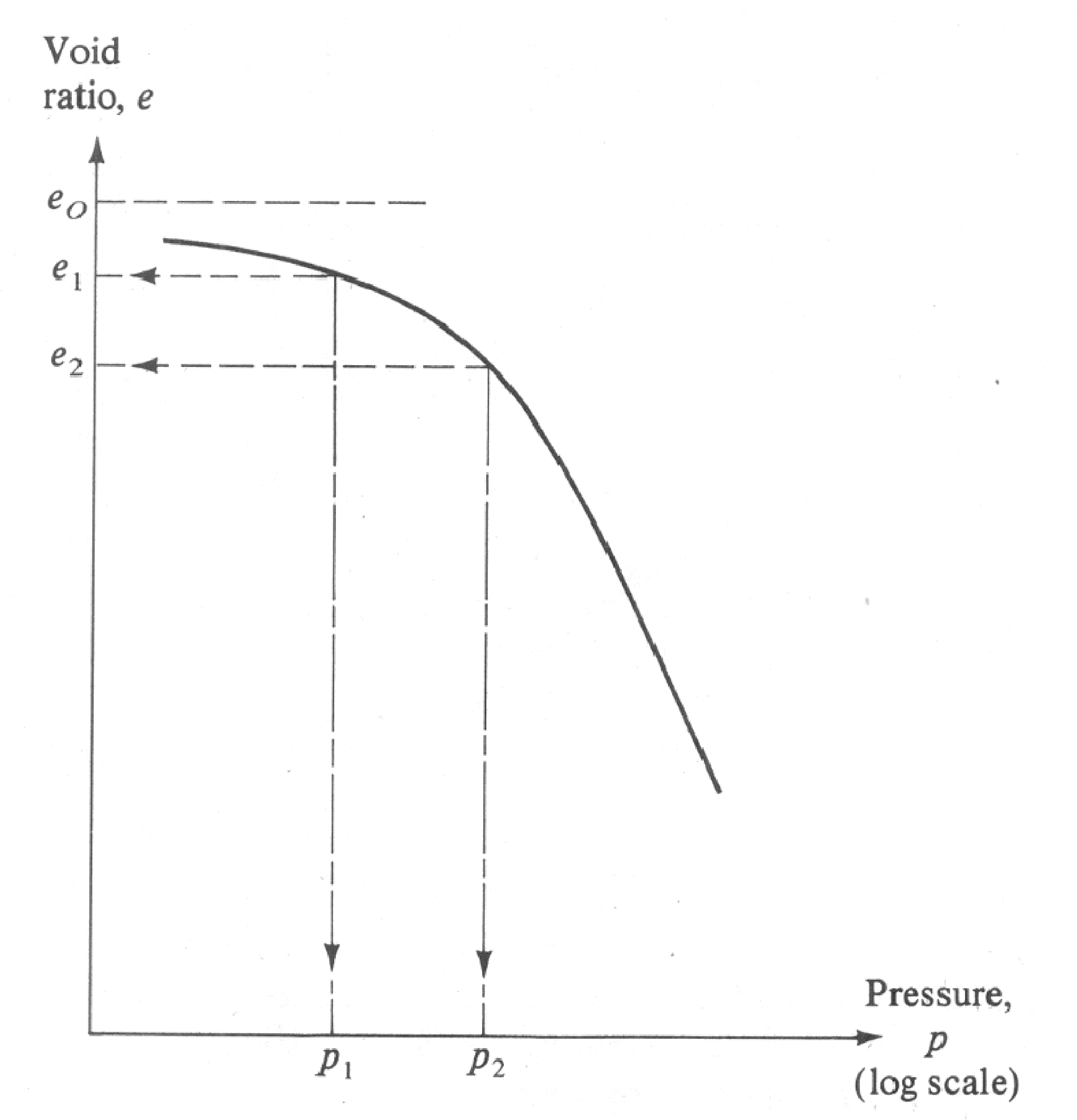
Compression Index (C_c):

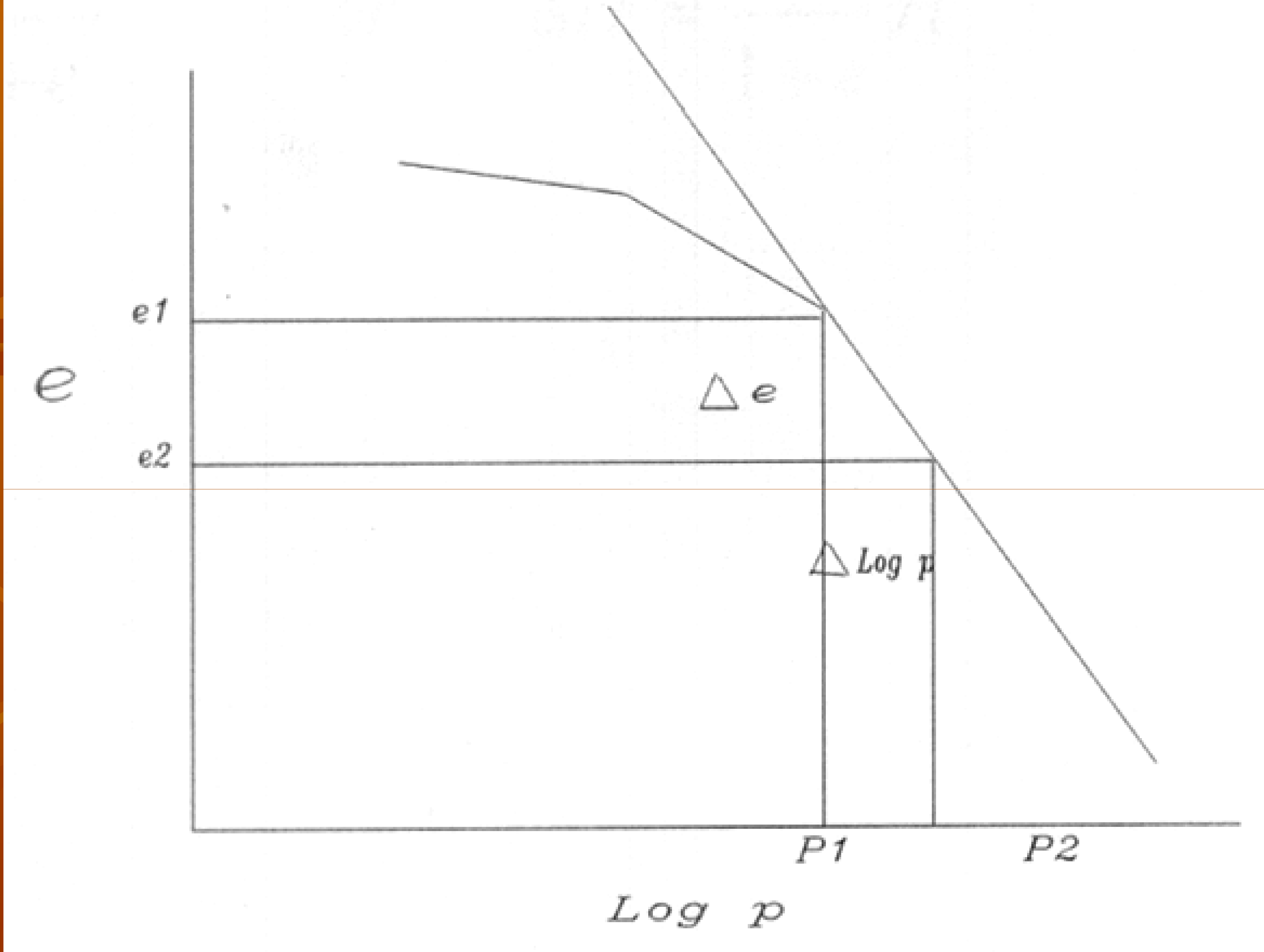
Slope of straight-line portion.

$$Cc = \frac{\Delta e}{\Delta \log_{10} \ p}$$

$$Cc = \frac{e_1 - e_2}{\log_{10} \ p_2 - \log_{10} \ p_1}$$

$$Cc = \frac{e_1 - e_2}{\log_{10} \left[\frac{p_2}{p_1} \right]}$$


Void
ratio, e
e_O
e_1
e_2
Pressure,
p
(log scale)
p_1
p_2


e1
e
Δe
e2
Δ Log p
P1
P2
Log p

Imperical relationship for Cc
Cc = 0.009 (L.L -10)

Final Settlement:

$$\Delta H = \left[\frac{\Delta e}{1+e_1} \right] H$$

$$e = \frac{Vv}{Vs} = \frac{V - Vs}{Vs} = \frac{V}{Vs} - 1$$

$$1 + e = \frac{V}{Vs}$$

Vs (I + e) =V
Vs (I + e) =AH (1)

Differentiating Eq. 1 w.r.t. e

$$A\frac{dH}{de} = Vs \qquad (2)$$

From Eq. 1 and 2

$$A\frac{dH}{de}(l+e)=AH$$

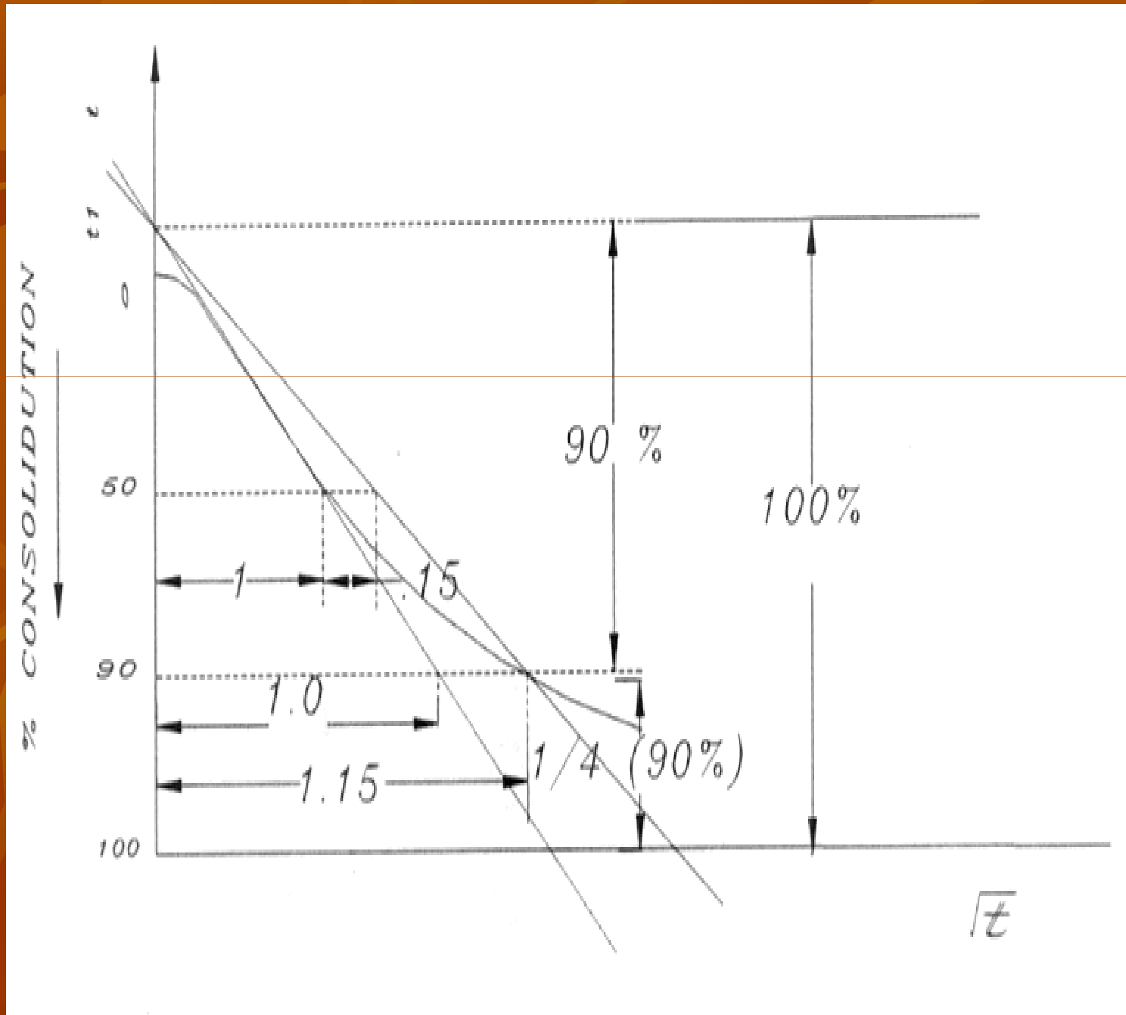
$$dH=\frac{H\quad de}{1+e}\qquad \text{or}\qquad \Delta H=\frac{\Delta e}{1+e}H$$

Determination of Zero and 100% Consolidation:

In practice only the primary consolidation is taken into consideration. The problem is to determine when and where in the time - consolidation graph the points of zero and 100% consolidation are located.

Taylor's Square Root of time fitting method:

In this method, all the dial readings are plotted on the ordinate axis and the corresponding square root of time on the abscissa as shown:



Taylor observed, that on the theoretical $\sqrt{t}$ ~ percent consolidation curve a straight line exists to beyond 50% consolidation, while at 90% consolidation the abscissa is 1.15 times the abscissa of the straight line produced. Using the Taylor's method, the straight-line t-t is drawn which coincide best the early part of the experimental curve. The intersection of the t-t line with the ordinate axis yield, the 'corrected' point of zero percent consolidation. Then a straight-line t_1-t_1 is drawn which at all the points has abscissa 1.15 times as great as that of the 1st line (t-t). This intersection of the 2nd line with the experimental curve is taken as the 90% consolidation point. Its time value is t_{90}. One ninth of the vertical distance between the corrected zero point and 90% point is added below the 90% point to give the 100% consolidation point of the primary consolidation.

Terzaghi's Theory of one Dimensional Consolidation:

Assumptions:

Terzaghi's theory for the determination of rate of consolidation of a saturated soil mass subjected to a static steady load is based on the following assumptions:

1. The soil is homogeneous and isotropic.
2. The soil is fully saturated.
3. The soil particles and water in the voids are incompressible.
4. The consolidation occurs due to expulsion of water from the voids.
5. The co-efficient of permeability of the soil has the same value at all the points and remains constant during the entire period of consolidation.
6. Darcy's law is valid throughout the consolidation process.
7. Soil is laterally confined and the consolidation takes place only in the axial direction.
8. Drainage of water occurs in the vertical direction only.
9. The time lag in consolidation is entirely due to the low permeability of the soil.
10. There is a unique relationship between the void ratio and the effective stress and this relationship remains constant during the load increment. In other words, the co-efficient of compressibility and the co-efficient of volume change are constant.

Mathematical representation of Terzaghi's Theory:

$$\Delta H = mv\Delta pH\left[1-\frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{2n+1}e-(2nH)^2\frac{\pi^2}{4}\frac{Cvt}{H^2}\right]$$

ΔH = Reduction in thickness of compressible layer (consolidation settlement) after any time "t".

my = Co-efficient of compressibility

or

Co-efficient of volume decrease == Δe/ΔP (l/l +el)

Δe = Change in void ratio due to change in pressure ΔP

el = Initial void ratio

ΔP = The change in applied pressure

H = Thickness of compressible layer.

Cv = Co-efficient of consolidation = $\dfrac{k}{\gamma_w m_v}$

K = Co-efficient of permeability of soil
γ_w = Density of water
t = Time for consolidation
n = Any whole number depending on the time encountered.

For long term consolidation t = ∞
Therefore final settlement or ultimate settlement

$\Delta H = mv\ \Delta P\ H$

Degree of Consolidation (U)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Time factor (τv)	.008	0.031	0.071	0.126	0.197	0.287	0.403	0.567	0.848	0.9313

Degree of consolidation "U" = $\dfrac{\text{Change in thickness at any time 't'}}{\text{Final change in thickness}}$

Calculation of Settlement Due to One-Dimensional Primary Consolidation

Consider the system as shown in fig.

Thickness = H

Cross- sectional area = A

Existing average effective overburden pressure = Po

Increase of pressure = Δp

Let the primary settlement be S.

Thus, the change in volume can be given by

$$\Delta V = V_o - V_1 = H \cdot A - (H - S) \cdot A = S \cdot A$$

where V_0 and V_1 are the initial and final volumes, respectively

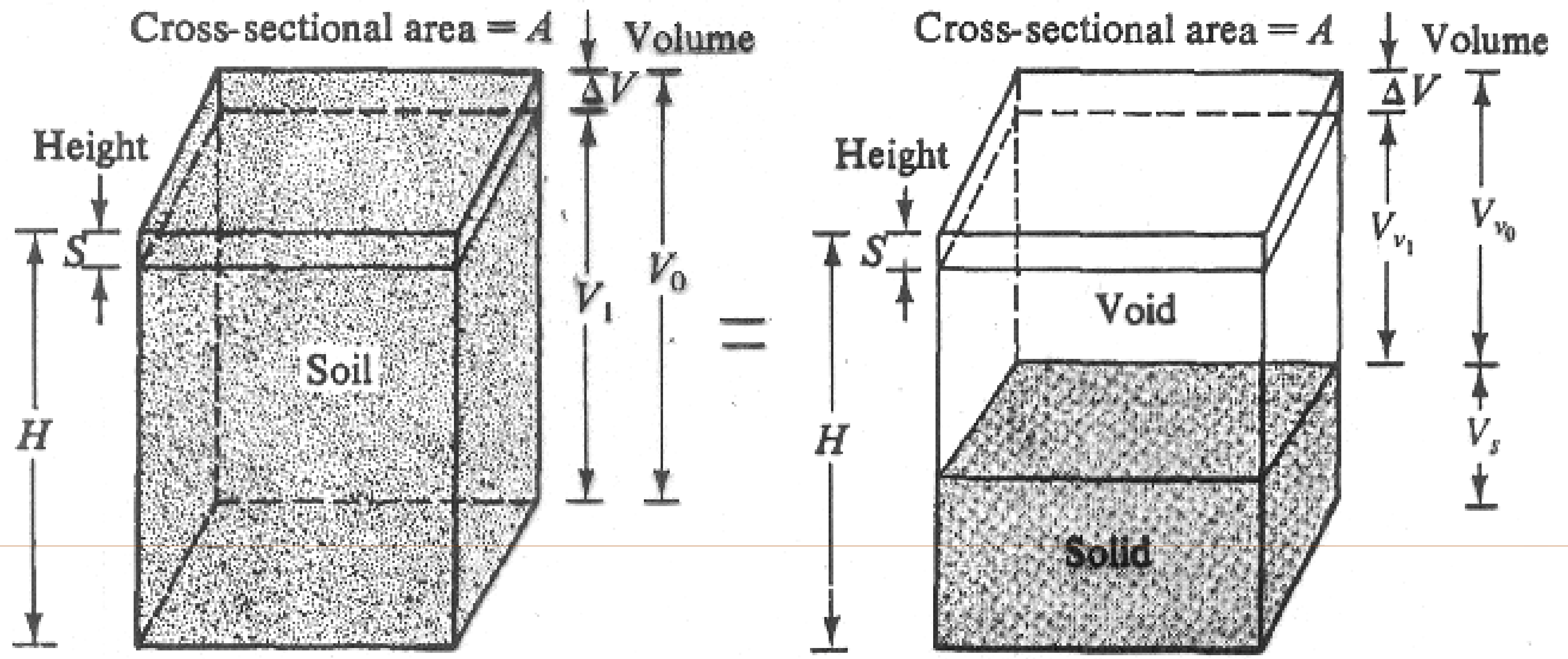


Figure Settlement caused by one-dimensional consolidation

However, the change in total volume is equal to the change in the volume of voids, ΔV_v. Thus

$$\Delta V = S \times A = V_{v0} - V_{v1} = \Delta v_v$$

(V_{v0} & V_{v1} are initial & final volumes of voids)

$\Delta_{Vv} = \Delta_e V_s$ Δ_e is change in void ratio

$$V_s = \frac{V_0}{1+e_0} = \frac{AH}{1+e_0}$$

e_0 is initial void ratio at volume V_0

Thus from above Eqs.

$$\Delta V = S \times A = \Delta_e V_s = \frac{AH}{1+e_0} \Delta_e$$

$$S = H \frac{\Delta_e}{1+e_0}$$

For Normally Consolidated Clays Exhibiting a Linear E-Log P Curve

$$\Delta_e = C_c[\log(p_o + \Delta p) - \log p_o]$$

where C_c= slope of the e-log *p* plot and is defined as the compression index Substitution of Eq. (7.24) in Eq. (7.23) gives

$$S = \frac{C_c H}{1+e_0}\log\left(\frac{p_0 + \Delta p}{p_0}\right)$$

For a thicker clay layer, it is more accurate if the layer is divided into sub-layers, and calculations for settlement are made separately for each layer. Thus, the total settlement for the entire layer can be given as

$$S = \sum\left[\frac{C_c H_i}{1+e_0}\log\left(\frac{p_{0(i)} + \Delta p_{(i)}}{p_{o(i)}}\right)\right]$$

Where,

H_i = thickness of sub-layer (*i*)
$P_{O(i)}$=Initial average effective overburden pressure for sub-layer (*i*)
$\Delta_{P(i)}$ = increase of vertical pressure for sub-layer (*i*)

In over consolidated clays (Figure), for $p_o + \Delta p \le p_c$ *field e~log p* variation will be along the line *cb,* the slope of which will be approximately equal to that for the laboratory rebound curve. The slope of the rebound curve, C_s is referred to as the *swell index.* So

$$\Delta e = C_s\,[\log (p_o + \Delta p) - \log p_o]$$

And we get the following Eqs.

$$S = \frac{C_c H}{1+e_0}\log\left(\frac{p_0+\Delta p}{p_0}\right)$$

If $p_0 + \Delta p > p_c$

$$S = \frac{C_c H}{1+e_0}\log\frac{p_c}{p_0} + \frac{C_c H}{1+e_0}\log\left(\frac{p_0+\Delta p}{p_c}\right)$$