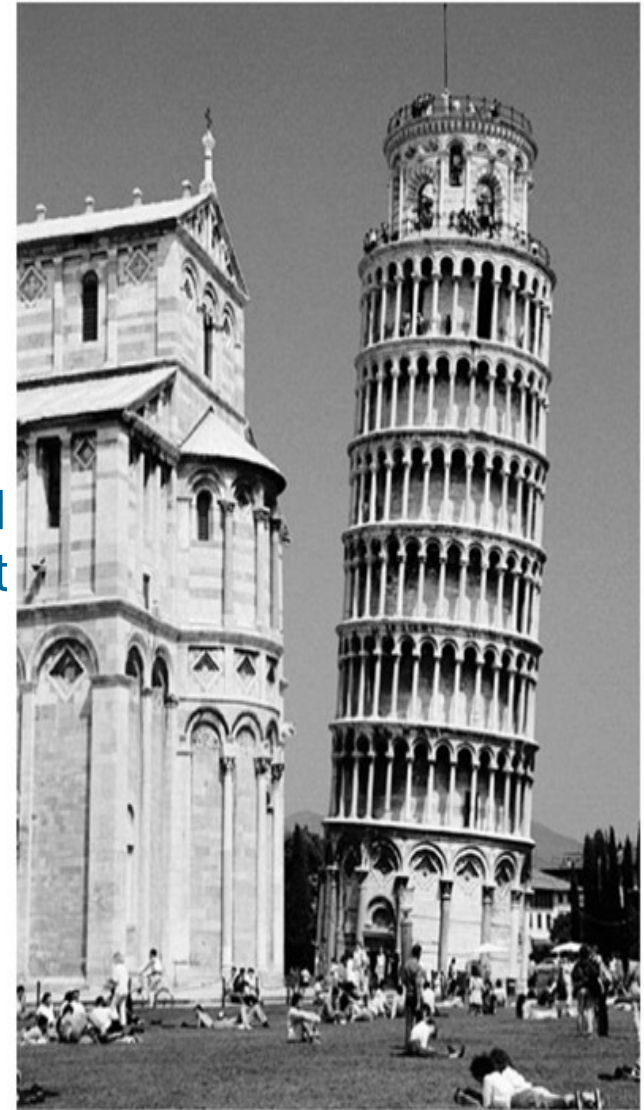


The background of the slide is white and decorated with festive elements. In the top-left corner, there is a green balloon with a green streamer and several yellow triangular confetti pieces. In the bottom-left corner, there is a purple balloon with a purple streamer and more yellow triangular confetti pieces. A light blue streamer also extends from the left side towards the center of the slide.

# **5.CONSOLIDATION OF SOILS**

# Practical situation

- Construction of the tower started in 1173, and by the end of 1178 when two-thirds of the tower was completed, it had tilted. Since then the tower has been settling differentially.
- The foundation of the tower is located about 3 m into a bed of silty sand that is underlain by 30 m of soft clay resting on a deposit of sand. A sand layer approximately 5 m thick intersects the clay.
- The structure of the tower is intact, but its function is impaired by differential settlement.



# SOIL SETTLEMENT

- The settlement of soil consist of
  - Immediate settlement (usually occur during construction)
  - Primary consolidation settlement (occurs during the life of the structure)
  - Secondary consolidation settlement or creep (occurs during the life of the structure but primary after primary consolidation)
- Immediate settlement is estimated using elastic theory
- Primary and secondary consolidation settlements are calculated based primarily on the one-dimensional consolidation theory proposed by Terzaghi (1925)

# COMPRESSIBILITY OF SOILS

## APPLICATION OF STRESSES TO ANY MATERIAL

### CAUSES STRAINS

In some material  
a certain amount of time required

Stress- strain- time  
relationships

Non elastic materials

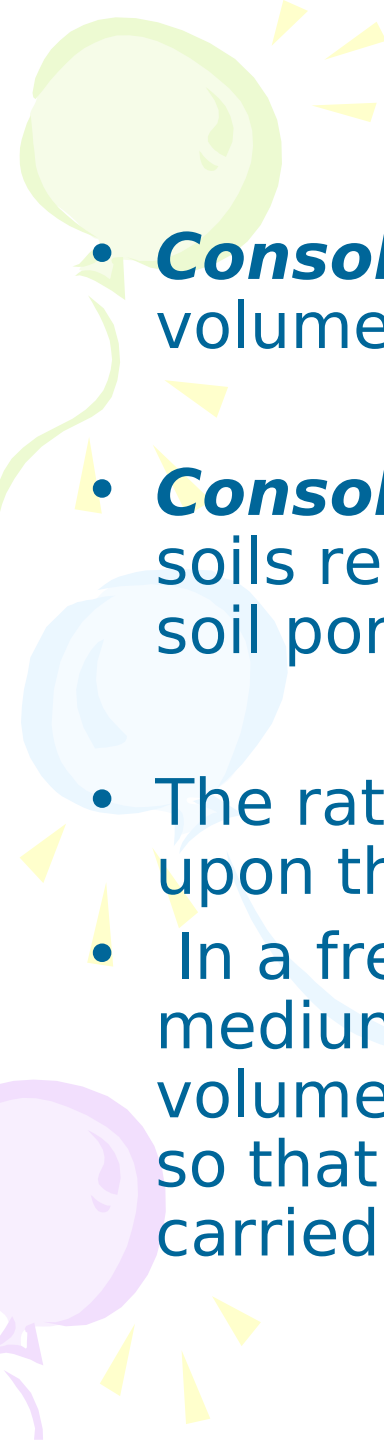
One-dimensional comp.  
of clay

In other materials strains are developed  
instantaneously

Stress and strains are proportional and  
Independent of time

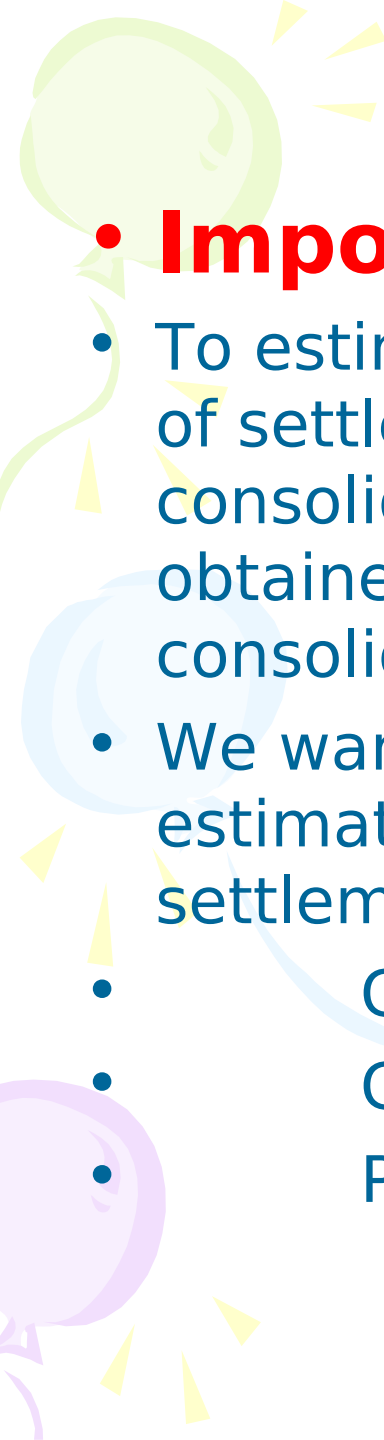
Theory of elasticity

Compression of granular  
soils



# ■ Consolidation

- **Consolidation** :is a gradual decrease of the volume of a soil at constant load.
- **Consolidation** is the time-dependent settlement of soils resulting from the expulsion of water from the soil pores.
- The rate at which the water can escape depends upon the permeability of the soil.
- In a free drained cohesion less soil, such as medium and coarse sand or gravel, the change in volume is generally slight and almost instantaneous so that very soon after its application the load is carried by the soil skeleton.



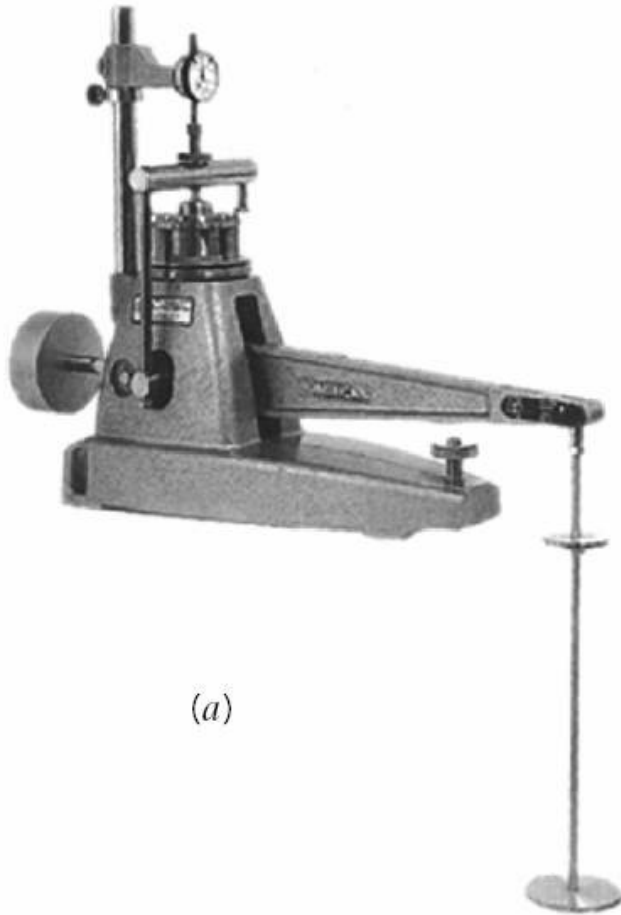
# • Consolidation Test

## • Importance

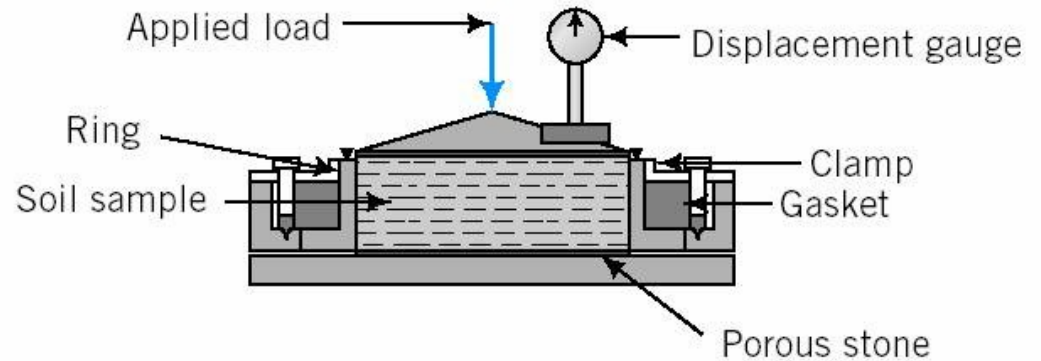
- To estimate the total settlement and the time rate of settlement, we need to obtain certain soil consolidation parameters . These parameters are obtained from a lab test called the one-dimensional consolidation test.
- We want to find the following parameters to estimate the amount and rate of consolidation settlement
  - Compression indices,
  - Coefficient of consolidation:
  - Past maximum vertical effective stress,

# Equipment:

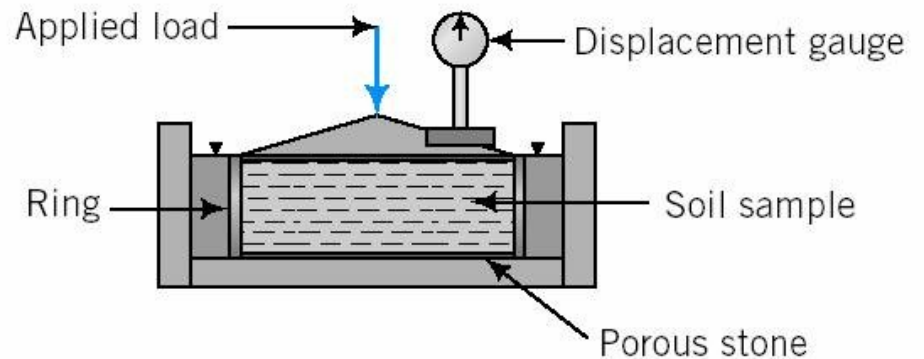
- The ring containing the soil sample can be fixed to the container by a collar (fixed ring cell, Figure b) or is unrestrained (floating ring cell, Figure c).



(a)



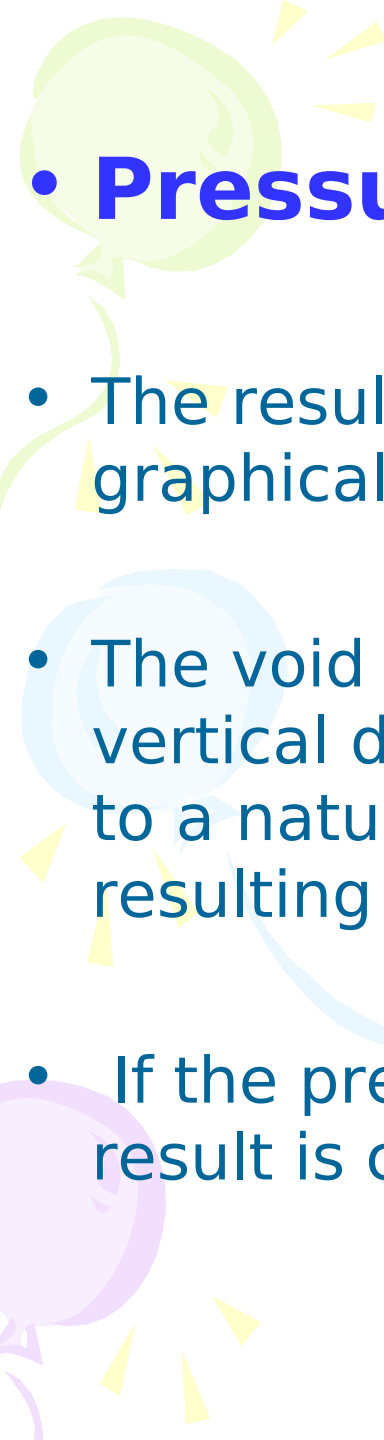
(b) Fixed ring cell



(c) Floating ring cell

- 
- The soil sample is mounted on a porous stone base, and a similar stone is placed on top to permit water, which is squeezed out of the sample to escape freely at the top and bottom.
  - Prior to loading, the height of the sample should be accurately measured. Also, a micrometer dial is mounted in such a manner that the vertical strains in the sample can be measured as loads are applied.
  - Loads are applied in steps in such a way that the successive load intensity,  $p$ , is twice the preceding one. The load intensities commonly used being  $\frac{1}{4}, \frac{1}{2}, 1, 2, 4, 8$  and  $16 \text{ kg/cm}^2$ .

- 
- Each load is allowing to stand until compression has practically ceased. The dial readings are taken at elapsed times of 0, 1/4, 1/2, 1, 2, 4, 8, 15, 30, 60, 120, 240, 480 and 1440 minutes from the time the new increment of load is put on the sample (or at elapsed times as per requirements).
  - After the greatest load required for the test has been applied to the soil sample, the load is removed in decrements to provide data for plotting the expansion curves of the soil in order to learn its elastic properties and magnitudes of plastic or permanent deformations.

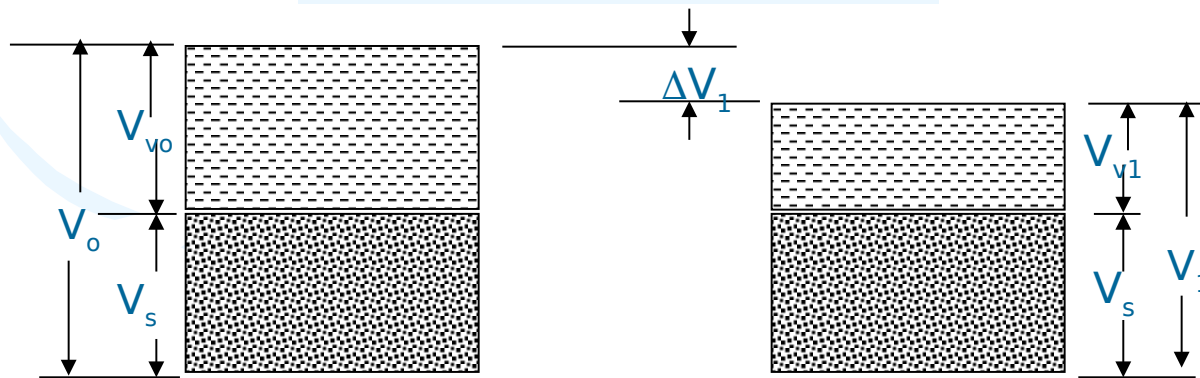


# • **Pressure Void Ratio Curves**

- The results of the consolidation test are presented graphically.
- The void ratio,  $e$ , is plotted to a natural scale in a vertical direction. If the intensity of pressure  $p$  is plotted to a natural scale in the horizontal direction, the resulting curve is designated as an  $e$ - $p$  curve.
- If the pressure is plotted to a logarithmic scale, the result is called an  $e$ -log $p$  curve.

- The equilibrium void ratio at any load increment can be found out by the change of void ratio methods as follows.
- In one-dimensional compression the change in height  $\Delta h$  per unit of original height  $h$  equals the change in volume  $\Delta V$  per unit of original volume  $V_o$ .

$$\frac{\Delta h_1}{h_o} = \frac{\Delta V_1}{V_o}$$



**a) Initial condition**

**b) Compressed**

The volume  $V$  can be expressed in terms of the void ratio as follows:

From fig .(a) we have  $V_o = V_s + V_{vo}$ , but  $e_o = V_{vo}/V_s \rightarrow V_{vo} = e_o V_s$

$$\begin{aligned}\rightarrow V_o &= V_s + e_o V_s \\ &= V_s(1 + e_o)\end{aligned}$$

Similarly, from fig. (b)  $V_1 = V_s(1 + e_1)$

Thus  $\Delta V_1 = V_o - V_1 = V_s(1 + e_o) - V_s(1 + e_1) = V_s(e_o - e_1)$

$$\frac{\Delta h_1}{h_o} = \frac{\Delta V_1}{V_o}$$

$$= \Delta e_1 / (1 + e_o)$$

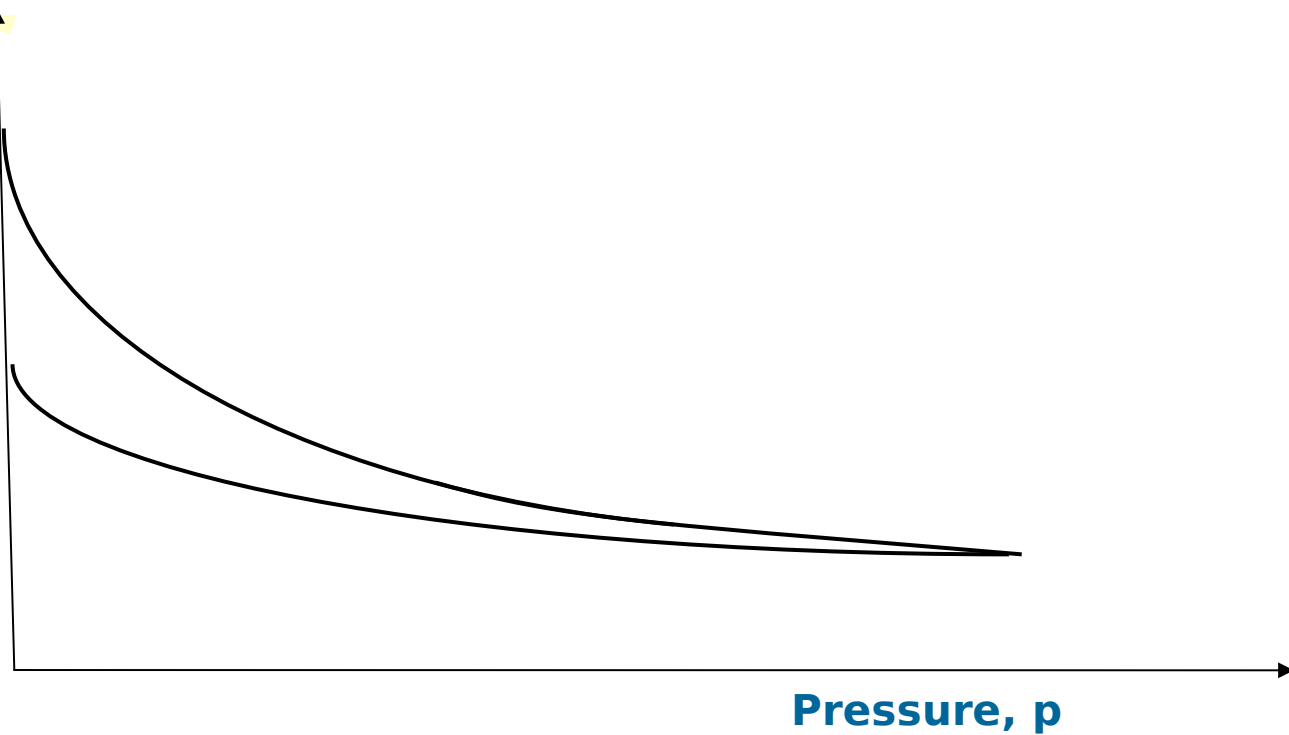
$$\Delta e_1 = \frac{\Delta h_1}{h_o} (1 + e_o)$$

$$e_o = \frac{V_o G_S \gamma_w}{W_S} - 1$$

$$e_1 = e_o - \Delta e_1$$

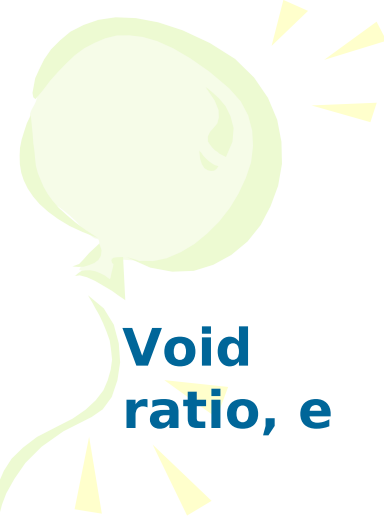
$$e_2 = e_1 - \left( \frac{\Delta h_2}{h_1} (1 + e_1) \right)$$

**Void  
ratio,  
 $e$**

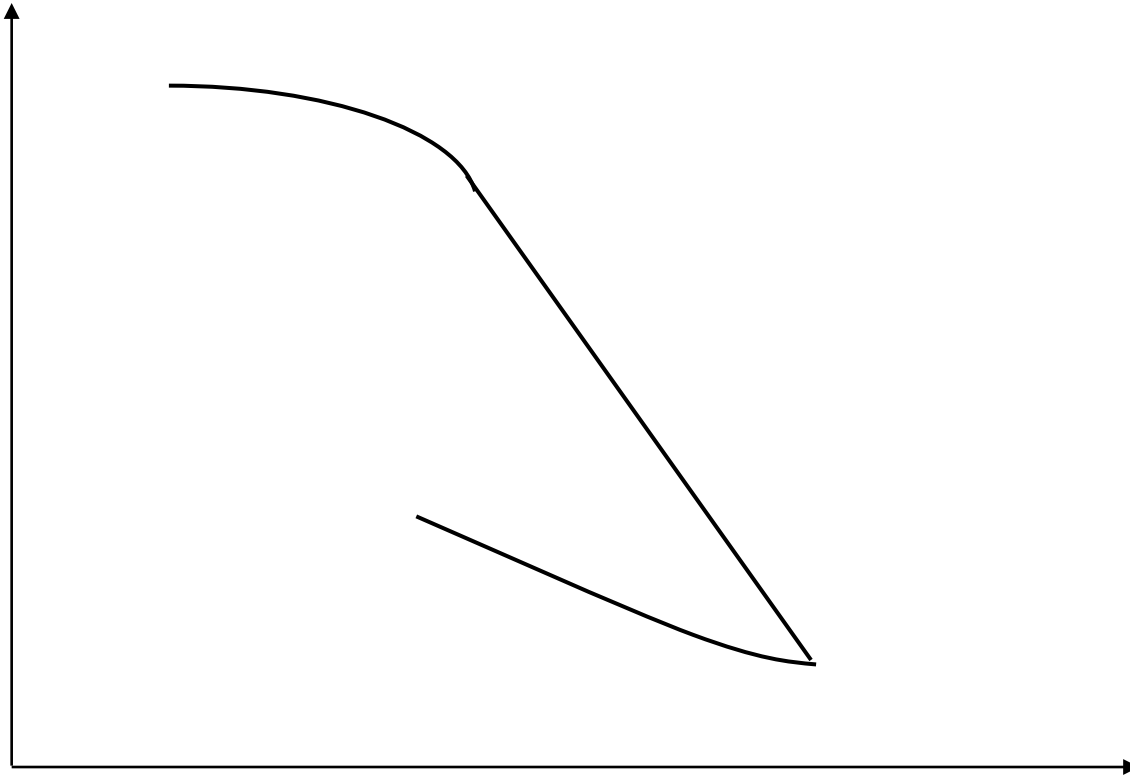


**Typical e-p curve**

Coefficient of compressibility,  $a_V = \frac{e_1 - e_2}{p_2 - p_1} = \frac{\Delta e}{\Delta p}$



**Void  
ratio,  $e$**

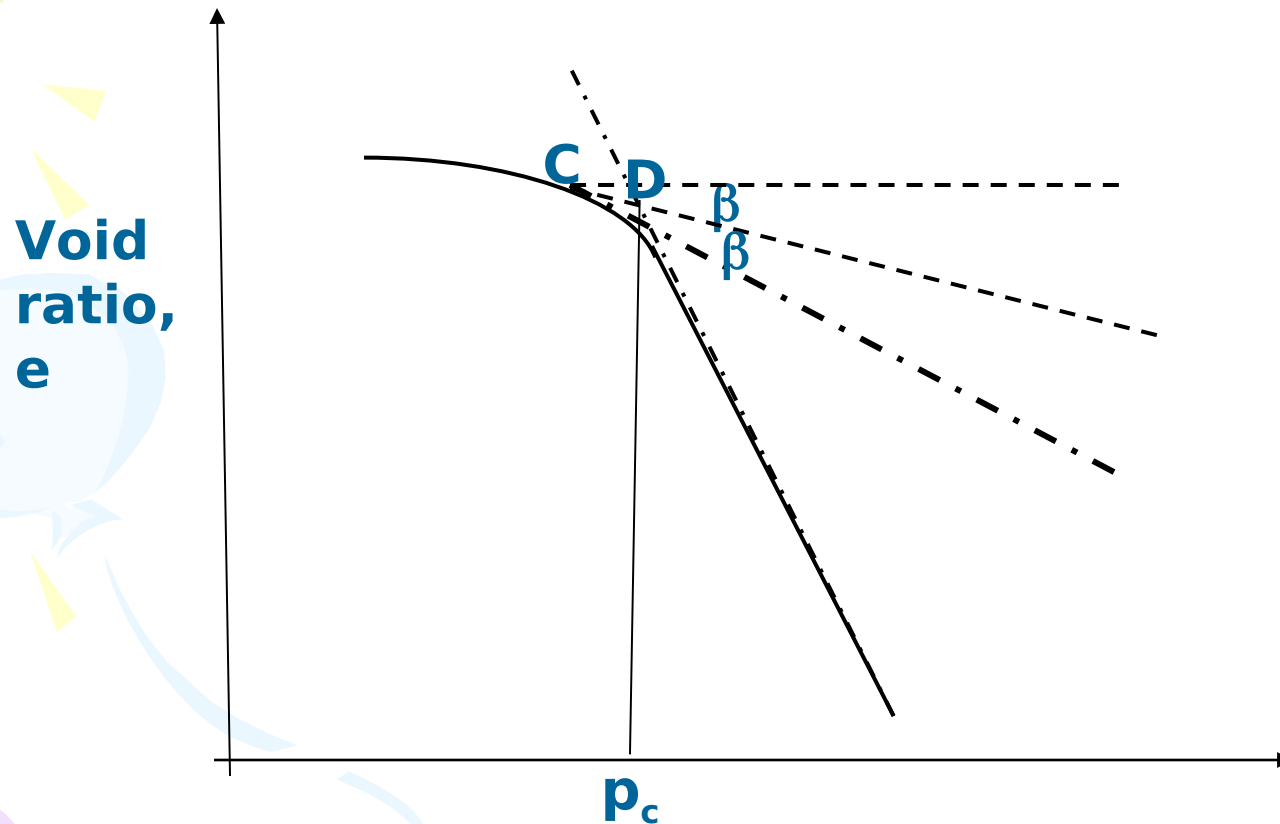


**Pressure,  $p$  (log scale)**

**Typical e-logP curve**

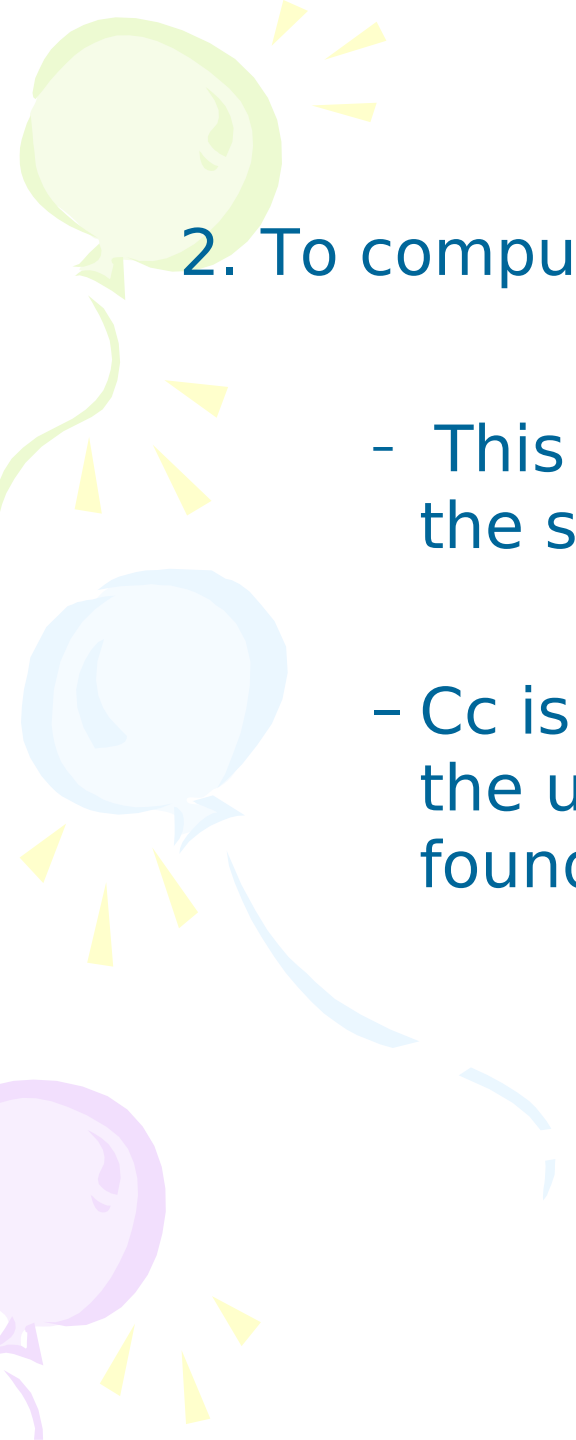
- e-logP plot used

# 1. To evaluate the pre-consolidation pressure(The maximum past effective overburden pressure)



- Select the point of max. curvature on the plot, say pt.C
- Draw a tangent and horizontal line through pt. C
- Bisect the angle formed by the tangent and horizontal line
- Produce the straight portion of the curve to cut the bisector at D
- The abscissa of Pt. D gives the pre-consolidation pressure,  $P_c$

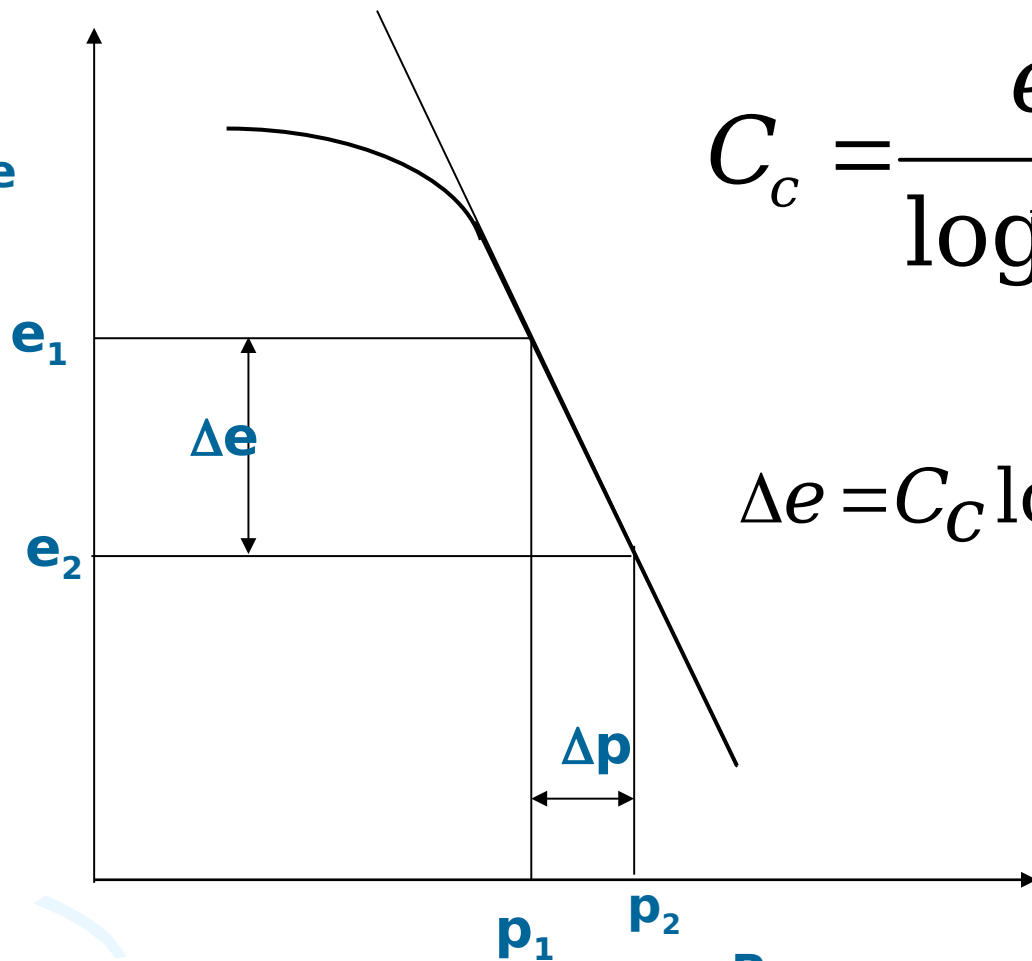
- 
- Based on the magnitude of the pre-consolidation pressure, one can define the following two conditions of a clay layer.
    - If  $P_c <$  the existing overburden pressure, then the clay layer is classified as Normally consolidated clay
    - If  $P_c >$  the existing overburden pressure, then the clay layer is classified as over consolidated.
  - In other words a clay is said to be normally consolidated if the present effective overburden pressure *Po is the* maximum pressure to which the layer has ever been subjected at any time in its history, whereas a clay layer is said to be overconsolidated if the layer was subjected at one time in its history to a greater effective overburden pressure,  $P_c$ , than the present pressure,  $P_o$ .

Three balloons (green, blue, and purple) are positioned vertically along the left margin of the slide. Each balloon has a string and several small yellow triangular flags attached to it.

2. To compute compression index,  $C_c$

- This is numerically equal to the slope of the straight portion of the  $e$ - $\log p$  curve.
- $C_c$  is an important index used to calculate the ultimate settlement of a foundation founded on a clay layer

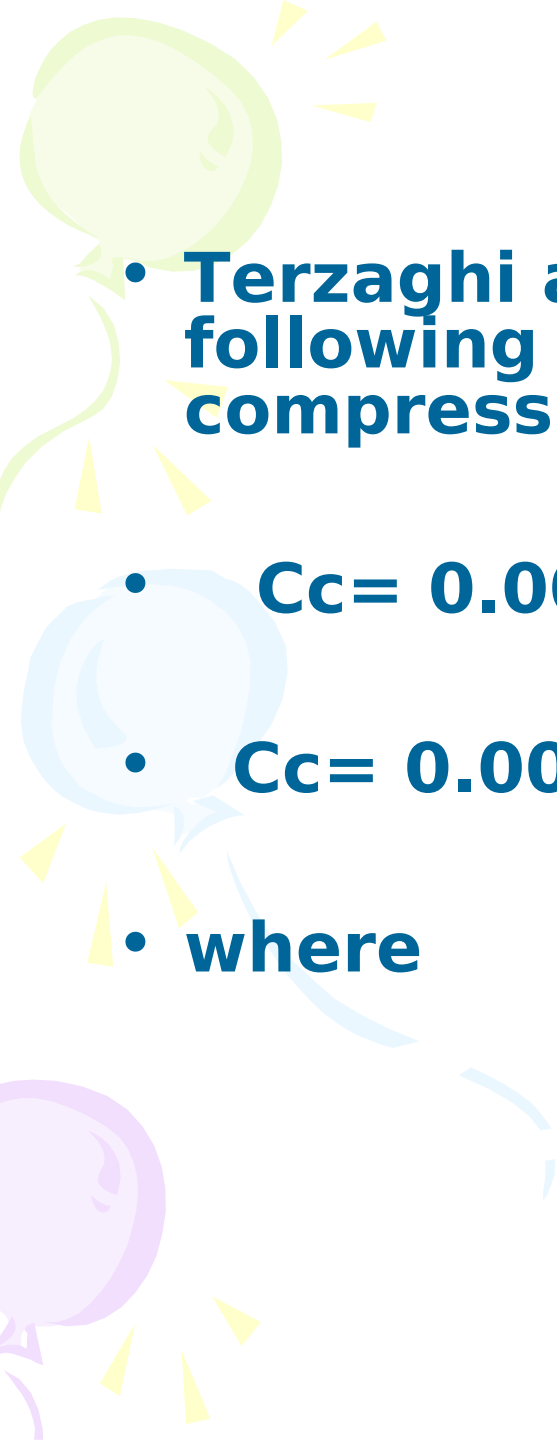
**Void ratio, e**



$$C_c = \frac{e_1 - e_2}{\log P_2 - \log P_1}$$

$$\Delta e = C_c \log \frac{P_1 + \Delta P}{P_1}$$

**Pressure, p (log scale)**



- **Terzaghi and peck (1967) suggested the following empirical expressions for compression index**

- **$C_c = 0.009 (\omega_l - 10)$  for undisturbed clays**

- **$C_c = 0.007 (\omega_l - 10)$  for remolded clays**

- **where  $\omega_l$  = liquid limit, in percent**

## • Calculation of One- Dimensional Consolidation Settlement

- Consider a saturated clay layer of thickness  $H$  and cross-sectional area  $A$  under an existing average effective overburden pressure  $P_o$ .
- Let the consolidation settlement due to an increase of pressure  $\Delta p$  be  $S$ . Thus the change in volume  $\Delta V$  is given by

$$\Delta V = V_o - V_1 = HA - (H - S)A = SA \dots\dots 1$$

$\Delta V = V_o - V_1 = \Delta V_v$ , But from the definition of void ratio we have  
 $\Delta V_v = V_s \Delta e \dots\dots 2$

$$V_o = V_s(1+e_o) \dots\dots 3$$

Combining equations 1,2 and 3 we have:

$$V_o \Delta e / (1+e_o) = SA$$

$$\rightarrow V_o \Delta e / (1+e_o) = S V_o / H$$

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



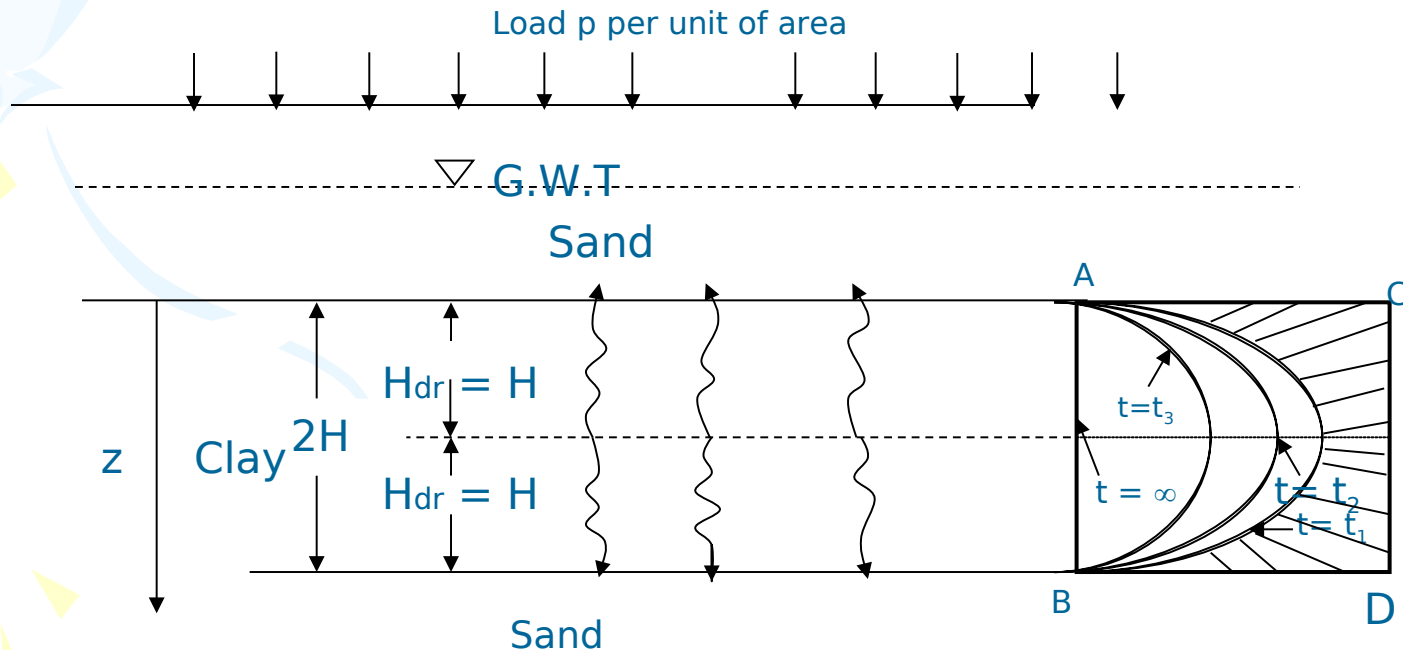
**For normally consolidated clays exhibiting a linear  $e - \log p$  relation**

$$\Delta e = C_c \left[ \log(P_o + \Delta P) - \log P_o \right]$$

$$S = \frac{C_c H}{1 + e_o} \log \frac{(P_o + \Delta P)}{P_o}$$

# • Basic Concepts of Terzaghi's Theory of Consolidation.

- To understand the basic concepts of Terzaghi's theory of consolidation, consider a clay of thickness  $2H$  located below the ground water level and between two highly permeable sand layers as shown in Fig below.



• Progress of consolidation process at a given point in the soil is indicated by  $U_z$ .

$$U_z = \frac{u_0 - u}{u_0} = 1 - \frac{u}{u_0}$$

consolidation at a point  
excess pressure  
pressure at time t

where:  $U_z$  = percent of

$U_0$  = Initial hydrostatic

$u$  = hydrostatic excess

The average percent consolidation of the entire layer at any time is numerically equal to the percent change in thickness or settlement. Then to estimate the rate of settlement it is necessary to establish the variation of  $u$  with time

# •Mathematical Expression and Solution of Terzaghi's Theory of Consolidation

$$\frac{du}{dt} = C_V \frac{d^2u}{dz^2} \dots\dots\dots 4$$

(Refer principles & practices of soil Mechanics and Found.Eng.by V.N.S.Murthy from page 255-257)

**Where:**  $C_V = \frac{k}{\gamma_w m_v} = \frac{k(1+e)}{\gamma_w a_v}$

**Where :**  $C_v$  = Coefficient of consolidation

$K$  = Coefficient of permeability

$m_v$  = Coefficient of volume compressibility =  $a_v/(1+e)$

$a_v$  = Coefficient of compressibility

## Boundary conditions

$$u = 0 \text{ at } z = 0, \quad u = 0 \text{ at } z = 2H, \quad \text{at } t = 0, \\ u = u_0 = p$$

Equation 4 has been solved for the boundary conditions described above and the solution is obtained by means of Fourier Series and presented in the following form.

$$u = \sum_{m=0}^{m=\infty} \frac{2u_0}{M} \sin\left(\frac{Mz}{H}\right) e^{-M^2 T} \quad \text{.....2}$$

Where:  $u$  = excess pore water pressure ,  
 $m$  = is an integer ,  
 $u_0$  = initial excess pore water pressure ,

$$M = \frac{\pi}{2} (2m+1) \quad T = \frac{C_v t}{H^2_{dr}}, \text{ time factor (dimensionless)}$$

• The average degree of consolidation  $U$  for the entire depth of the clay layer at any  $t$  can be written as

$$U = \frac{S_t}{S} = 1 - \frac{u/u_o}{1} = 1 - \frac{\frac{1}{2H} \int_0^{2H} u dz}{u_o}$$

$U$  = Avg. degree of consolidation  
 $S_t$  = Settlement of the layer at time  $t$   
 $S$  = ultimate settlement due to primary consolidation.

• Substitution of the expression for excess pore water pressure  $u$  gives

$$U = 1 - \sum_{m=0}^{\infty} \frac{2}{M^2} e^{-M^2 T}$$

Often the first term (with  $m=0$ ) provides a solution of sufficient precision for practical purpose, and tabular values can be made once and for all in terms of percent consolidation  $U$  and  $T$  by rearranging and solving the above equation for  $T$ , to obtain

$$T = \frac{\ln(2/M^2) - \ln(1-U)}{M^2}$$

# Factors Affecting Time Rate of Consolidation

- According to Terzaghi's mathematical analysis of consolidations, the time rate of consolidation of clay stratum depends on the,
  - Thickness of clay layer
  - Number of drainage face
  - Permeability of the soil
  - Magnitude of the consolidating pressure acting on the clay layer.

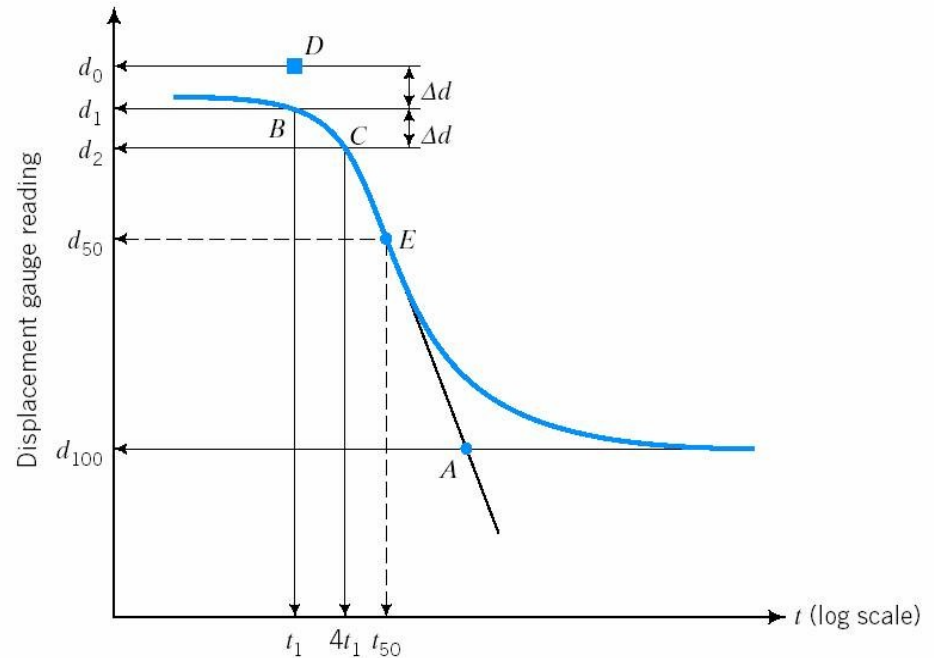
# • **Coefficient of Consolidation**

- **For a given load increment, the coefficient of consolidation,  $C_v$ , can be determined from laboratory observation of time versus dial reading.**
- **There are two graphical procedures;**
  - **the logarithm-of-time fitting method proposed by Cassagrande and Fedum and**
  - **the square-root-of- time fitting method proposed by Taylor.**

# FINDING $C_v$ USING CASAGRANDE AND FADUM (1940) METHOD

29

- Procedure FOR ROOT TIME METHOD
  - Project the straight portions of the primary consolidation and secondary compression to intersect at A. The ordinate of A,  $d_{100}$ , is the displacement gage reading for 100% primary consolidation.
  - Correct the initial portion of the curve to make it a parabola. Select a time  $t_1$ , point B, near the head of the initial portion of the curve and then another time  $t_2$ , point C, such that  $t_2 = 4t_1$
  - Calculate the difference in displacement reading,  $\Delta d = d_2 - d_1$ , between  $t_2$  and  $t_1$ .
  - Plot a point D at a vertical distance from B. The ordinate of point D is the corrected initial displacement gage reading,  $d_0$ , at the beginning of primary consolidation.
  - Calculate the ordinate for 50% consolidation as  $d_{50} = (d_{100} + d_0)/2$ .
  - Draw a horizontal line through this point to intersect the curve at E. The abscissa of point E is the time for 50% consolidation,  $t_{50}$ .



- Calculate

$$C_v = \frac{0.197H_{dr}^2}{t_{50}}$$

# Square- root-of- time fitting method

$$C_v = \frac{(0.848(H^2_{dr}))}{t_{90}}$$

Deformation  
dial reading

