

UNIT-4 Consolidation

Ref:-

Soil Mechanics

&

Foundation Engg.

B.C. Punmia.

Types of Compressibility:-

Immediate settlement:-

* Immediate settlement occurs in the soil upon load application and involves reduction in void space and rearrangement of the soil particles in response to that load.

Primary consolidation:-

* This process begins when soil is fully saturated. Due to increase in effective stress over the saturated soil mass, pore pressure increase. As a result, expulsion of pore water occurs if drainage facility is provided. Primary consolidation is completed when expulsion of pore water stops.

* During the process of consolidation, soil remains saturated and flow of water is under laminar condition i.e. $Re < 1$

Secondary consolidation:-

* After completion of primary consolidation when expulsion of pore water is stopped and load continues to act, then at very slow rate further volume changes may be reduced which is due to plastic readjustment of solids.

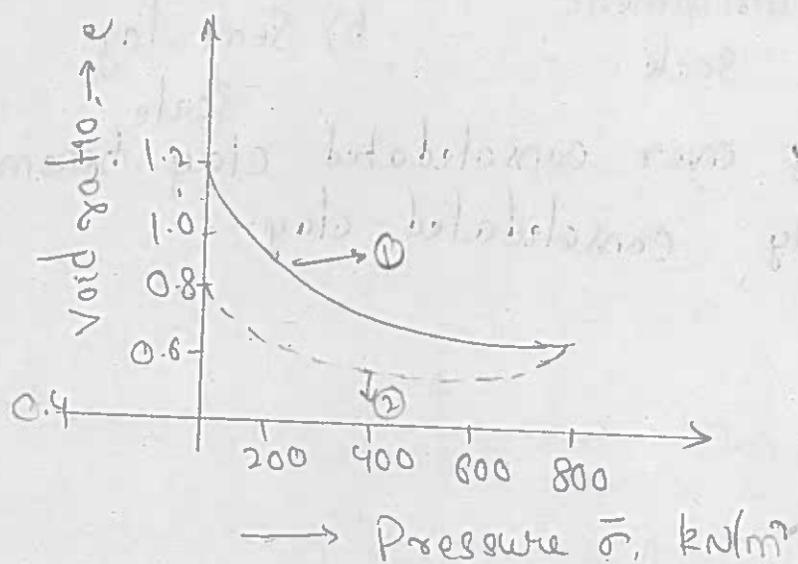
This is called secondary consolidation and it

is time-dependent, which is much slower than primary consolidation.

* Secondary consolidation is more in plastic soils and is highly plastic clays.

Stress history of clay:-

- Virgin compression curve is the curve between pressure and void ratio for initial loading.
- Whereas rebound curve is the curve between pressure and void ratio for unloading.
- Under equal range pressure, clay exhibits high compressibility when compared to sand.
- The rebound due to pressure release at the time of unloading is very less.
- The virgin compression curve and the rebound curve, involving one cycle of loading and unloading are plotted on the graph.



where,

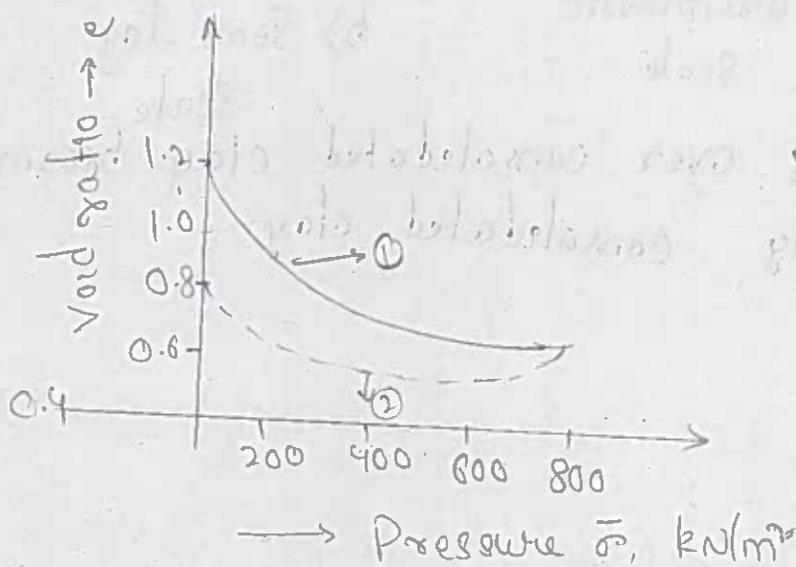
- 1) Virgin compression curve
- 2) Rebound curve

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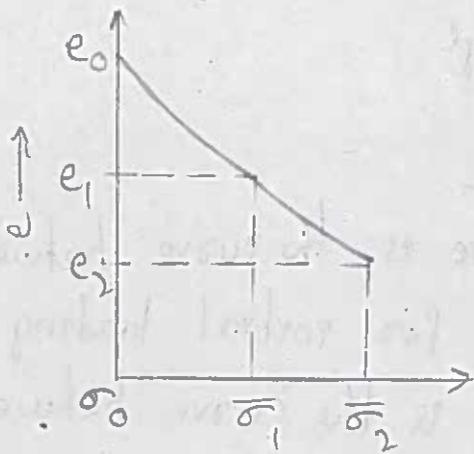


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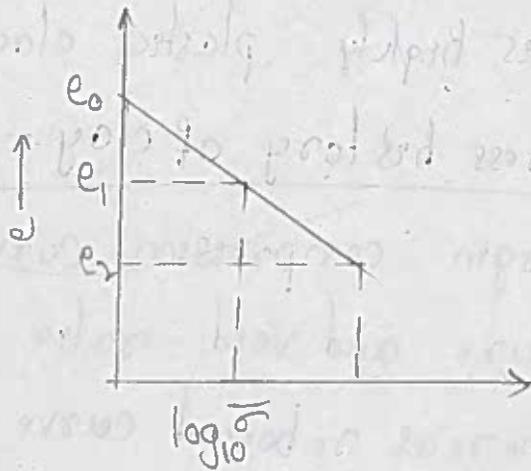
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$e-p$ and $e-\log(p)$ Curves:-

1) Normally consolidated clay:-

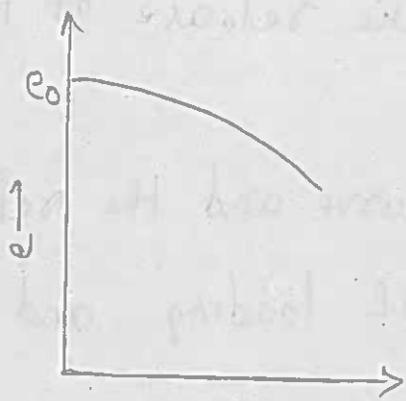


a) On arithmetic scale

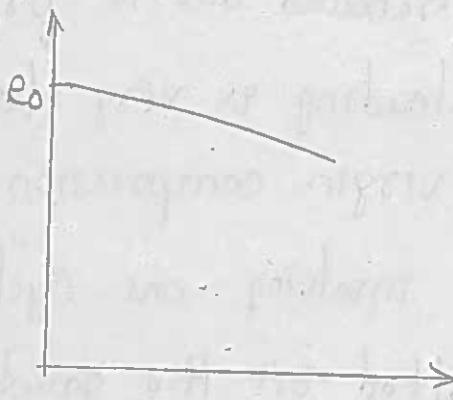


b) On semi-log scale

2) Over consolidated clays:-

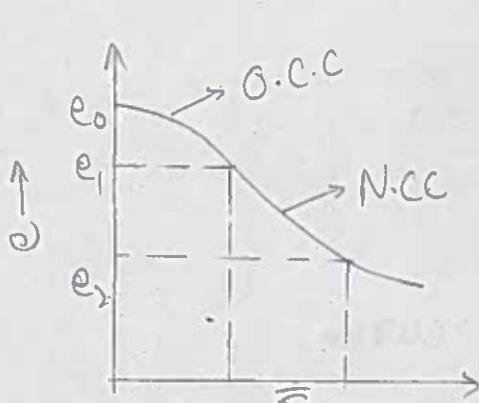


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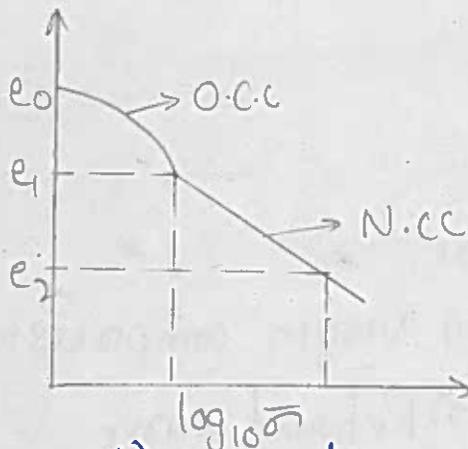


b) Semi-log scale

3) Initially over consolidated clay becomes Normally consolidated clay:-

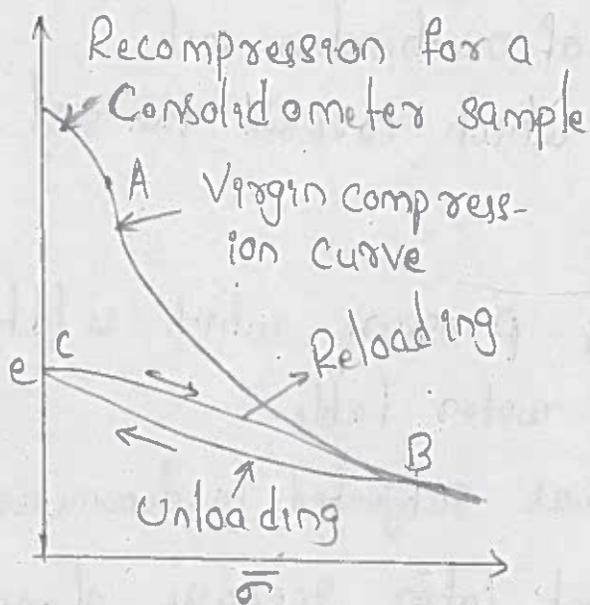


a) On arithmetic scale

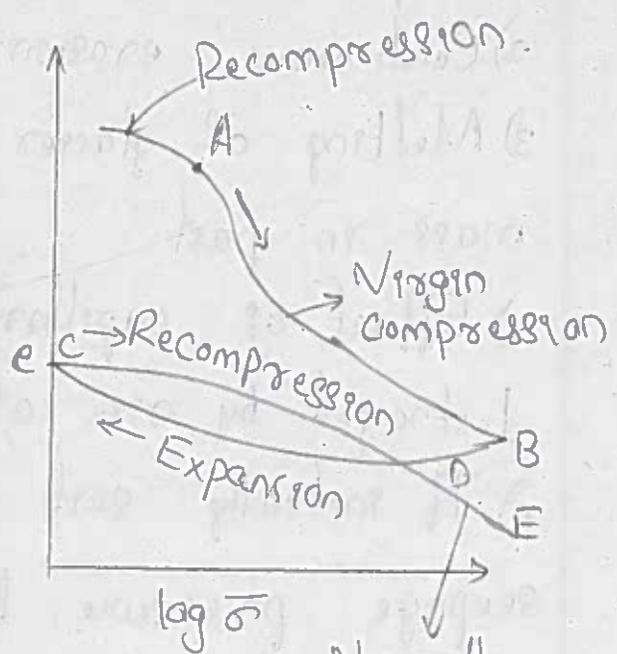


b) Semi-log scale

4) When clay undergoes recompression and the compression:-



(a)



Normally Consolidated

(b)

Normally consolidated soil:-

* Normally consolidated soils are those which are loaded for the first time to the present applied effective stress. It means past applied effective stress was ~~over~~ lower than the present applied effective stress. Such soils are more compressible.

Over consolidated soil:-

* Over consolidated soils are those which have been subjected to effective stress in the past greater than present applied effective stress. The over consolidation / normal consolidation can be differentiated using over consolidation ratio.

Causes of Over-Consolidation or Pre-consolidation:

- 1) In the past, overburden pressure or surcharge was placed, which is removed later.
- 2) Continuous erosion of overburden soil.
- 3) Melting of glaciers which covered the soil mass in past.
- 4) Effect of capillary pressure which is later destroyed by rise of water table.
- 5) If initially soil was subjected to downward seepage pressure but later seepage stops then effective stress reduces.

Pre consolidation pressure:-

→ The maximum pressure to which an over-consolidated soil had been subjected in the past is known as the preconsolidation pressure or over-consolidation pressure ($\bar{\sigma}_c$).

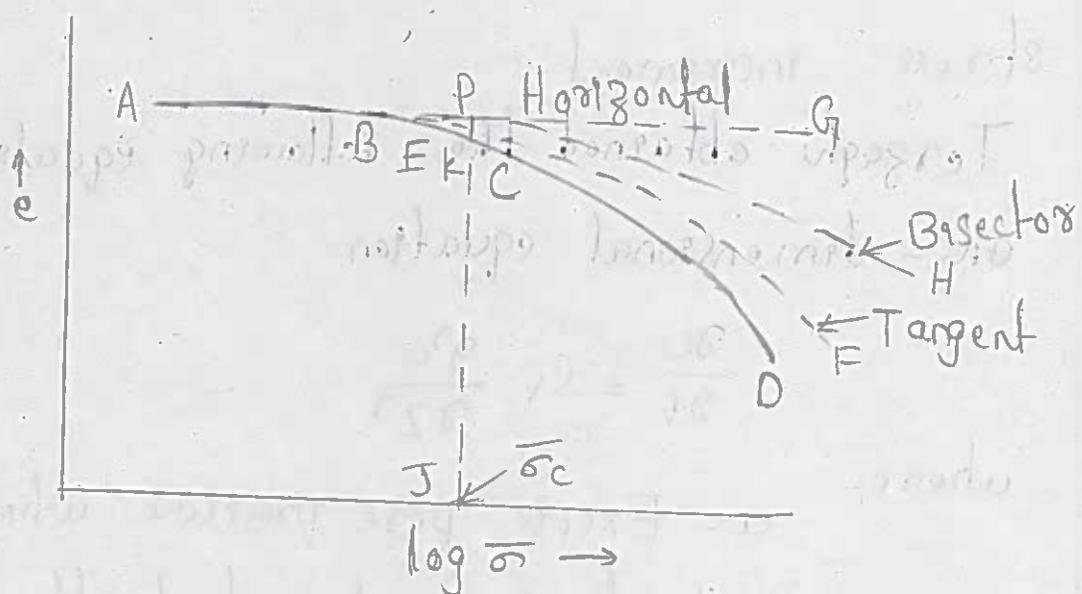
→ When a soil specimen is taken from a natural deposit, the weight of overlying material is removed.

→ This causes an expansion of the soil due to a reduction in pressure.

→ Thus the specimen is generally preconsolidated or over consolidated.

* The procedure consists of the following steps:-

- 1) Determine the point E on the curve where the curvature is maximum, i.e., the radius of curvature is minimum.
- 2) Draw the tangent EF to the curve at E.
- 3) Draw horizontal line EG at E.
- 4) Bisect the angle between the tangent EF and the horizontal EG, and draw the bisector EH.
- 5) Produce back the straight line portion CD of the curve and determine the point of intersection P of the bisector EH and the backward extension of CD.
- 6) Draw the vertical PJ through P which cuts the log $\bar{\sigma}$ axis at J. The point J indicates the preconsolidation pressure $\bar{\sigma}_c$.
- 7) The vertical PJ cuts the curve at point K. The portion ABK of the curve represents recompression curve and portion KCD as virgin compression curve.



Terzaghi's 1-D Consolidation theory:-

Assumptions:-

- 1) The soil is homogenous and isotropic
- 2) Soil is fully saturated and flow is laminar is Darcy's law is valid.
- 3) The soil remain saturated along during the process of consolidation.
- 4) The strain produced due to stress applied is small. It means there will be no change in soil structure.
- 5) The flow is essentially one-dimensional and no change in area cross-sectional occur
- 6) The hydrodynamic lag is considered while plastic lag is ignored.
- 7) There is a unique relationship between void ratio and effective stress, independent of time, i.e.,

$$\Delta e = -a_v \Delta \bar{\sigma}$$

where a_v is assumed constant over the stress increment.

Terzaghi obtained the following equation for one-dimensional equation.

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

where,

u = Excess pore pressure which is developed due to applied effective stress.

$\frac{\partial u}{\partial t}$ = Rate of change of pore pressure*

C_v = coefficient of consolidation which depends upon type of soil. It determines rate of consolidation.

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

where,

k = coefficient of permeability

m_v = coefficient of volume compressibility

Coefficient of Consolidation:-

- * The term coefficient of consolidation (C_v) is used to indicate the combined effect of the permeability and compressibility of soil on the rate of volume change.

Equation of coefficient of consolidation:-

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

- * The unit of coefficient of consolidation (C_v) is cm^2/sec .

where,

γ_w = unit weight of water.

Square root of time fitting method:-

- * This method, developed by Taylor, utilizes theoretical relationship between u and $\sqrt{T_v}$
- * The relationship is linear up to value of u equal to about 60%.

* It was observed that at $U=90\%$, value of $\sqrt{T_v}$ is 1.15 times value obtained by extension of the initial straight line portion.

* A curve is plotted from consolidation test results between dial gauge reading (R) as ordinate and \sqrt{T} .

Logarithm of time fitting method:-

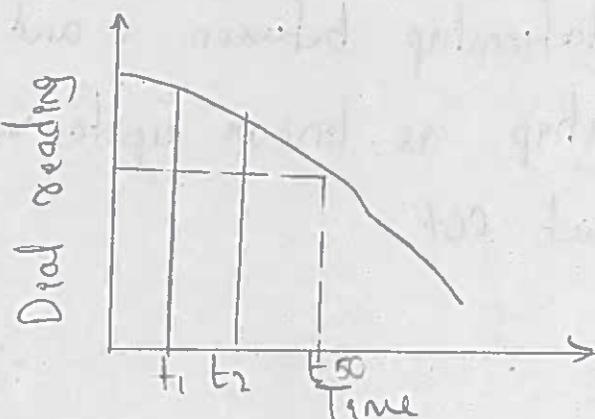
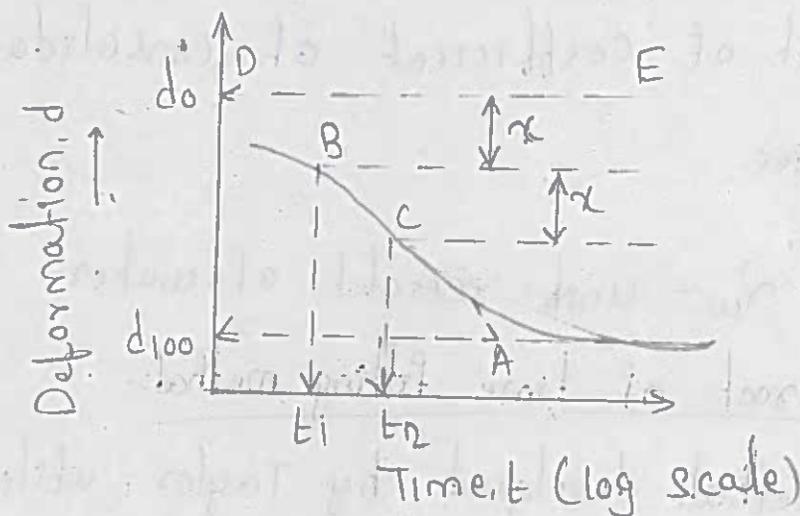
* This method, developed by A. Casagrande, determines $100\% U$ on semi log plot of laboratory time consolidation curve by theoretical curve between U and $\log T_v$.

* Construct a plot of dial reading vs log of time

→ H_0 = Initial height of specimen

→ $R_{start} = 0$

→ R_{50} = Determine from the plot



Computation of total settlement:-

* The total settlement of a loaded soil can be grouped into two broadly, components

- a) Immediate settlement (S_i)
- b) Consolidation settlement (S_{con})

a) Immediate settlement (S_i):-

→ It occurs almost immediately after the load is imposed, as a result to distortion of the soil without any volume change.

→ It is due to compression, expulsion of pore air, elastic deformation of soils and squeezing of water.

For cohesion soils:-

$$S_i = \frac{H_0}{C_s} \log_{10} \left(\frac{\bar{\sigma}_0 + \Delta \bar{\sigma}}{\bar{\sigma}_0} \right)$$

$$C_s = 1.5 \frac{C_r}{\bar{\sigma}_0}$$

where, C_r = static cone resistance in kN/m^2

$\bar{\sigma}_0$ = initial effective stress due to overburden pressure at the centre of layer.

H_0 = total thickness of soil layer initially

$\Delta \bar{\sigma}$ = increase in effective stress at the centre of layer due to application of load.

For cohesive soils:-

→ The immediate elastic deformation below the corner of a rectangular base foundation is given by

$$S_i = \frac{q \cdot B (1 - \mu^2)}{E_s} \cdot I_f$$

where,

q = pressure at the base of foundation

B = width of foundation (dimension)

μ = Poisson's ratio of soil

= 0.3 to 0.45

E_s = Young's modulus of soil

I_f = influence factor

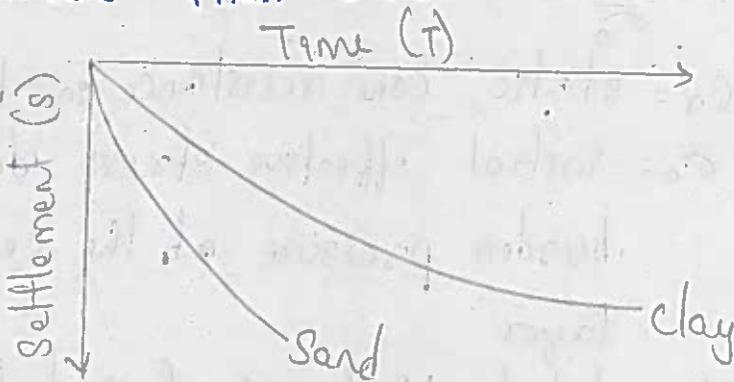
b) Consolidation settlement (S_{con}):-

→ The total consolidation of settlement of soil can be further divided into two parts.

i) Settlement due to primary consolidation (S_c)

ii) Settlement due to secondary consolidation (S_s)

→ The total consolidation settlement and the time of consolidation in clays is much greater than that of sand. Hence clays are more compressible than sand.



Time rate of settlement:-

* When a soil is subjected to an increase in effective stress, the pore water is squeezed from a sponge, and the basic concept is rate of settlement of the surface of clay layers.

→ According to square root method

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

→ According to logarithmic time fitting method

$$C_v = \frac{T_{50} \cdot d^2}{t_{50}}$$

where,

C_v = coefficient of consolidation

d = length of drainage path

T_{90} and T_{50} are the corresponding values of time factor for 90% and 50% consolidation.

Q:- The coefficient of consolidation (C_v) of a clay was found to be $0.955 \text{ mm}^2/\text{min}$. The final consolidation settlement for a 5m thick layer of this clay was calculated as 280mm. Assuming a uniform initial excess pore-water pressure distribution and permeable layers to be present both above and below the clay layer, compute the settlement time for

i) 90% primary consolidation. (Take $T_v = 0.848$ for $U = 90\%$)

ii) Settlement of 100mm.

Given data,

Ultimate settlement $\Delta H = 280 \text{ mm}$

$C_v = 0.955 \text{ mm}^2/\text{min}$

thickness of clay layer, $H_0 = 5 \text{ m}$

Since drainage layer is available on above and below the clay layer

Length of drainage path = $d = \frac{5}{2}$

$$= 2.5 \text{ m}$$

i) Let t_{90} be the time required for 90% settlement,

$$T_v(90) = \frac{C_v \cdot t_{90}}{d^2}$$

$$T_v(90) = 0.848$$

$$0.848 = \frac{0.955 \times t_{90}}{2500^2}$$

$$t_{90} = \frac{0.848 \times 2500^2}{0.955}$$

$$= 5549738.2 \text{ min or } 3854 \text{ days}$$

ii) Let 'U' be the degree of consolidation

for $\Delta h = 100 \text{ mm}$

$$U = \frac{\Delta h}{\Delta H} = \frac{100}{280} = 0.357$$

Since $U < 0.5$, Hence $T_v = \frac{\pi}{4} U^2$ is applicable

$$T_v = \frac{\pi}{4} \times 0.357^2 = 0.1$$

Let 't' be the time corresponding to 35.7% Consolidation

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

$$0.1 = \frac{0.955}{2500^2} \times t$$

$$t = \frac{0.1 \times 2500^2}{0.955} \text{ min}$$

$$= \frac{0.1 \times 2500^2}{0.955 \times (60 \times 24)}$$

$$t = \underline{\underline{456.87 \text{ days}}}$$