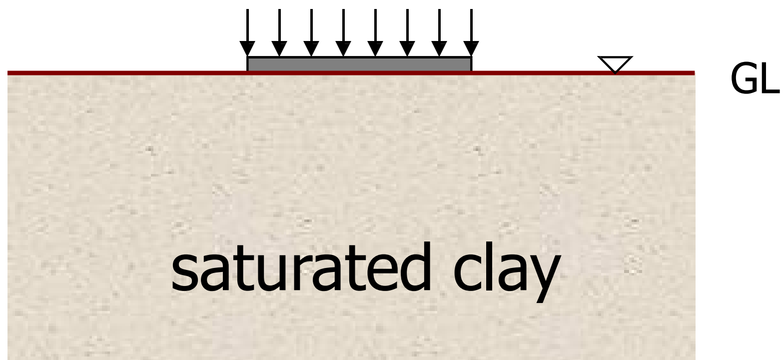
Consolidation

What is Consolidation?

When a saturated clay is loaded externally,



The reduction in volume will takes place by expulsion of water from voids over a long time

Compaction VS Consolidation

COMPACTION

1. Application of dynamic load.
2. Expulsion of air
3. Short Process

CONSOLIDATION

1. Application of static load.
2. Expulsion of water
3. Long Process

Types of Consolidation

The total compression of a saturated clay strata under excess effective pressure may be considered as the sum of

- 1. Immediate compression,
- 2. Primary consolidation, and
- 3. Secondary compression.

1. Immediate compression

The portion of the settlement of a structure which occurs more or less simultaneously with the applied loads is referred to as the initial or immediate settlement. This settlement is due to the immediate compression of the soil layer under undrained condition and is calculated by assuming the soil mass to behave as an elastic soil.

2. Primary consolidation

If the rate of compression of the soil layer is controlled solely by the resistance of the flow of water under the induced hydraulic gradients, the process is referred to as primary consolidation. The portion of the settlement that is due to the primary consolidation is called primary consolidation settlement or compression.

Change in volume by expulsion of water

3. Secondary Consolidation

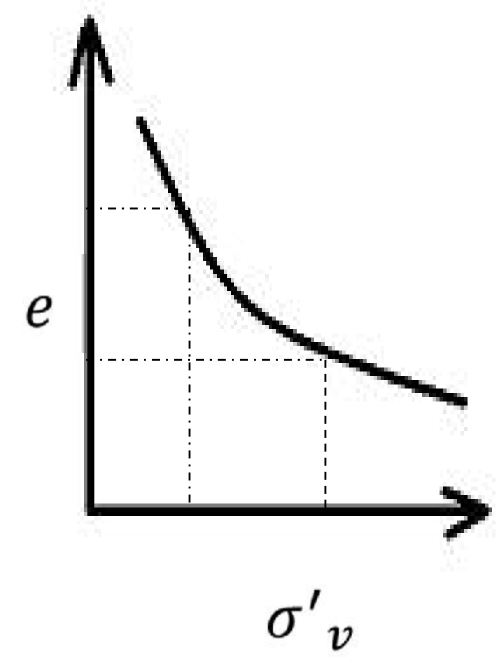
Compression due to the compression and rearrangement of the clay particles and clay layer. It is linear with logarithm of the time.

Basic definitions

- **1. coefficient of compressibility:**

Coefficient of compressibility is defined as change in void ratio due to per unit change in effective stress. It is denoted by (a_v)

$$a_v = -\frac{\Delta e}{\Delta \sigma'_v}$$

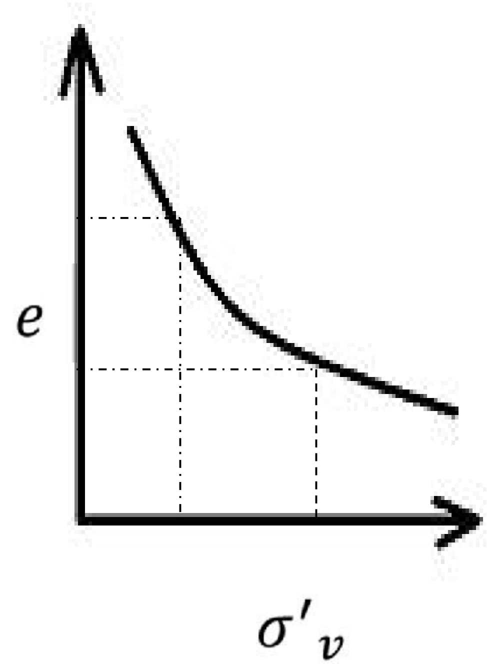


Basic definitions

2. Coefficient of Volume Change:

The coefficient of volume change is defined as the volumetric strain per unit increase in effective stress. It is denoted by (m_v)

$$m_v = -\frac{\frac{\Delta V}{V}}{\Delta \sigma'}$$

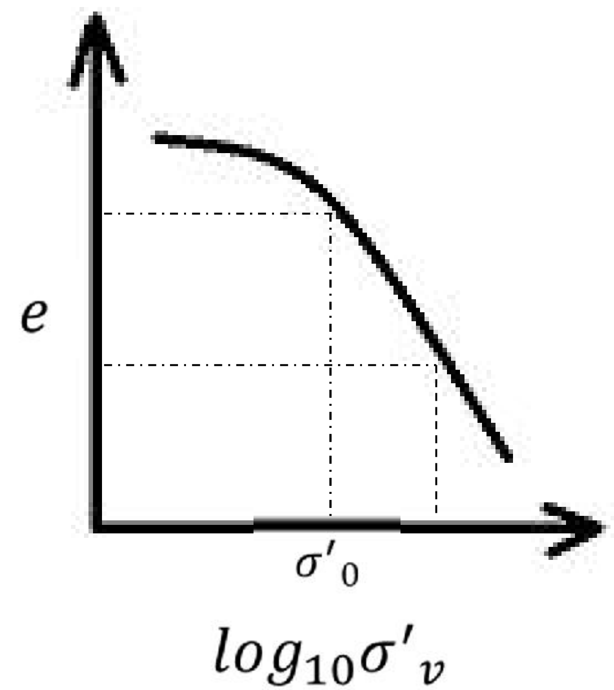


Basic definitions

3. Compression Index:

The compression index is defined as the slope of the linear portion of the void ratio (e) verses $log_{10}\sigma'_v$. It is denoted by (c_c)

$$c_c = -\frac{\Delta e}{log_{10}(\frac{\sigma'_0 + \Delta\sigma'_v}{\sigma'_0})}$$



Terzaghi and Peck

c_c=0.009 (LL-10) for undisturbed

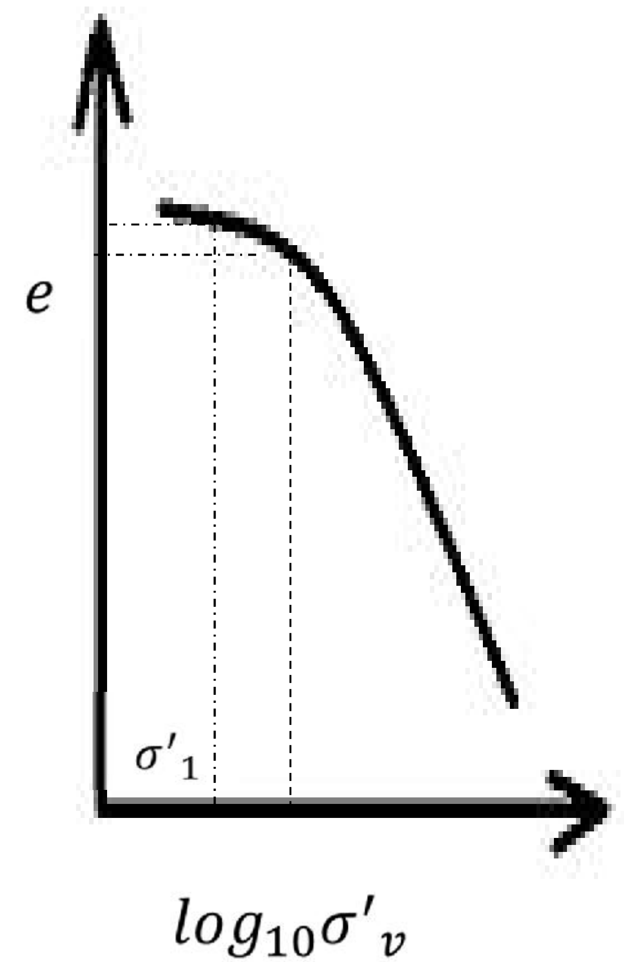
c_c=0.007 (LL-10) for remolded

Basic definitions

4. Recompression Index:

The recompression index is defined as the slope during reloading (c_r)

$$c_r = -\frac{\Delta e}{log_{10}(\frac{\sigma'_2}{\sigma'_1})}$$



Terzaghi and Peck

c_c=0.009 (LL-10) for undisturbed

c_c=0.007 (LL-10) for remolded

Normally consolidated clay and over consolidated clay

- **Normally consolidated clay:** A soil is normally consolidated when it has never been subjected to stress higher than the present stress.
- **Over consolidated clay:** A soil which has experienced higher stress in the past than the present stress.
- Cause of over consolidation

I. Removal of the overburden; excavation, erosion, landslide etc.

I. Removal of the structure

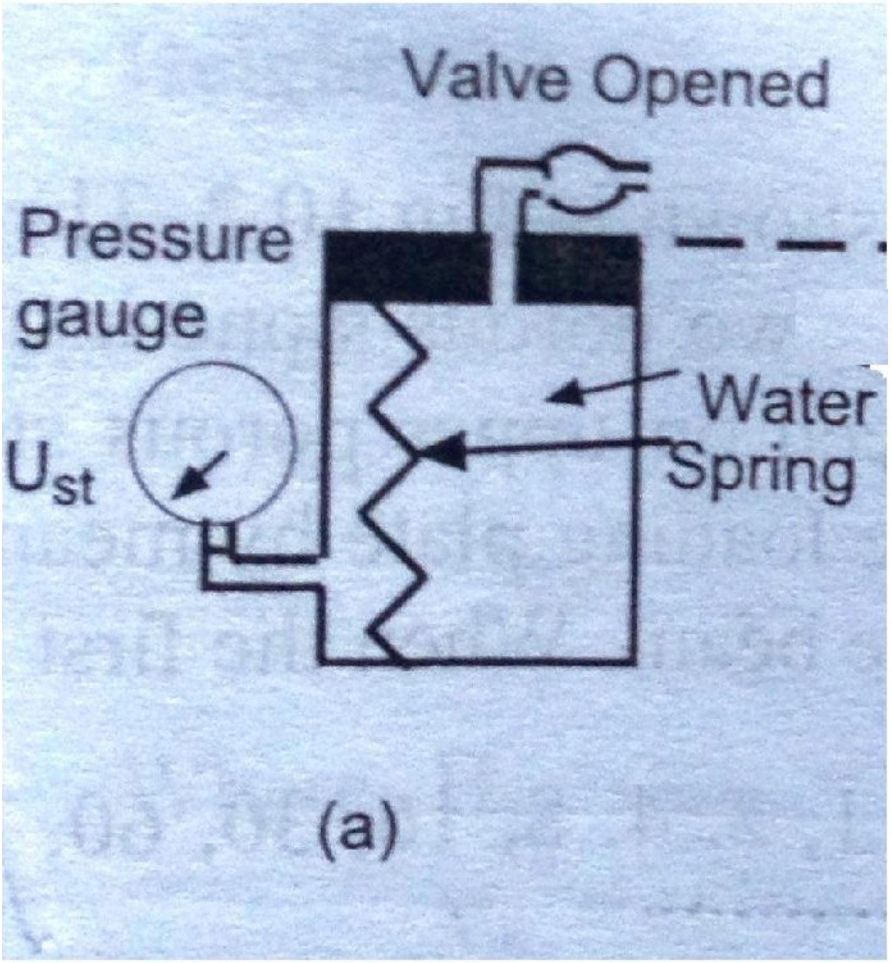
II. Variation in pore water pressure

Is not type of soil but is pressure history.

$$OCR = \frac{past\ stress}{present\ stress} > 1$$

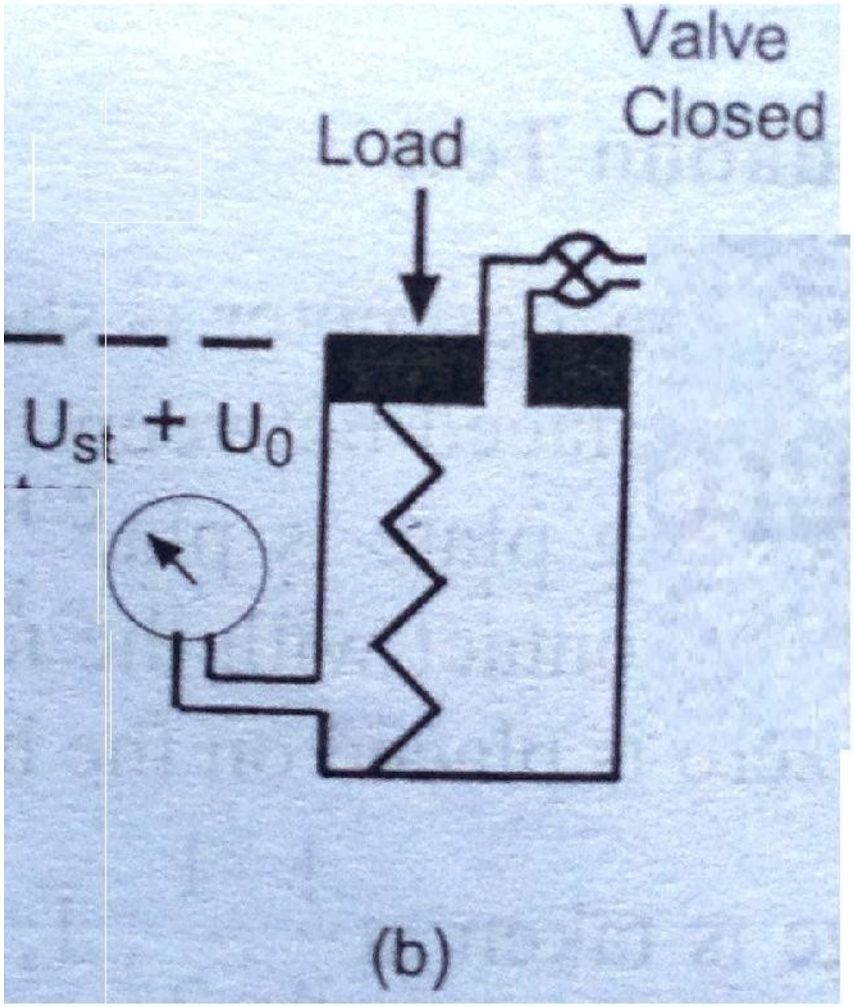
Over consolidated clay

Terzaghi spring analogy



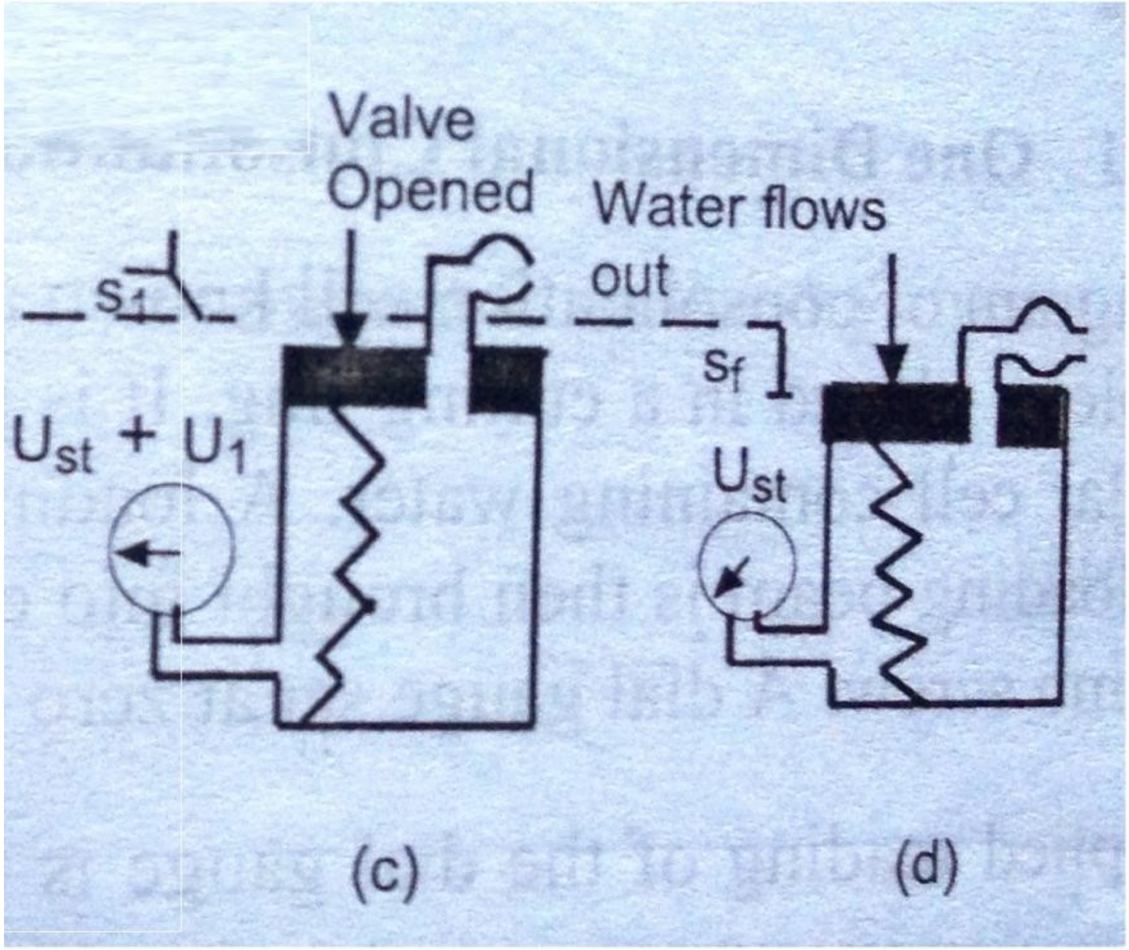
- Valve is opened; The system is equilibrium.

This is similar to the soil before loading



- The valve is closed and the piston is loaded. The pressure increase in the gauge is equal to the increased load.

This is similar to the condition just after loading.



When valve is opened the piston start to move down and the pore water pressure is gauge reduced. The applied load is now share by both spring and water.

At final stage; pressure gauge shows Ust pressure all load is taken by spring.

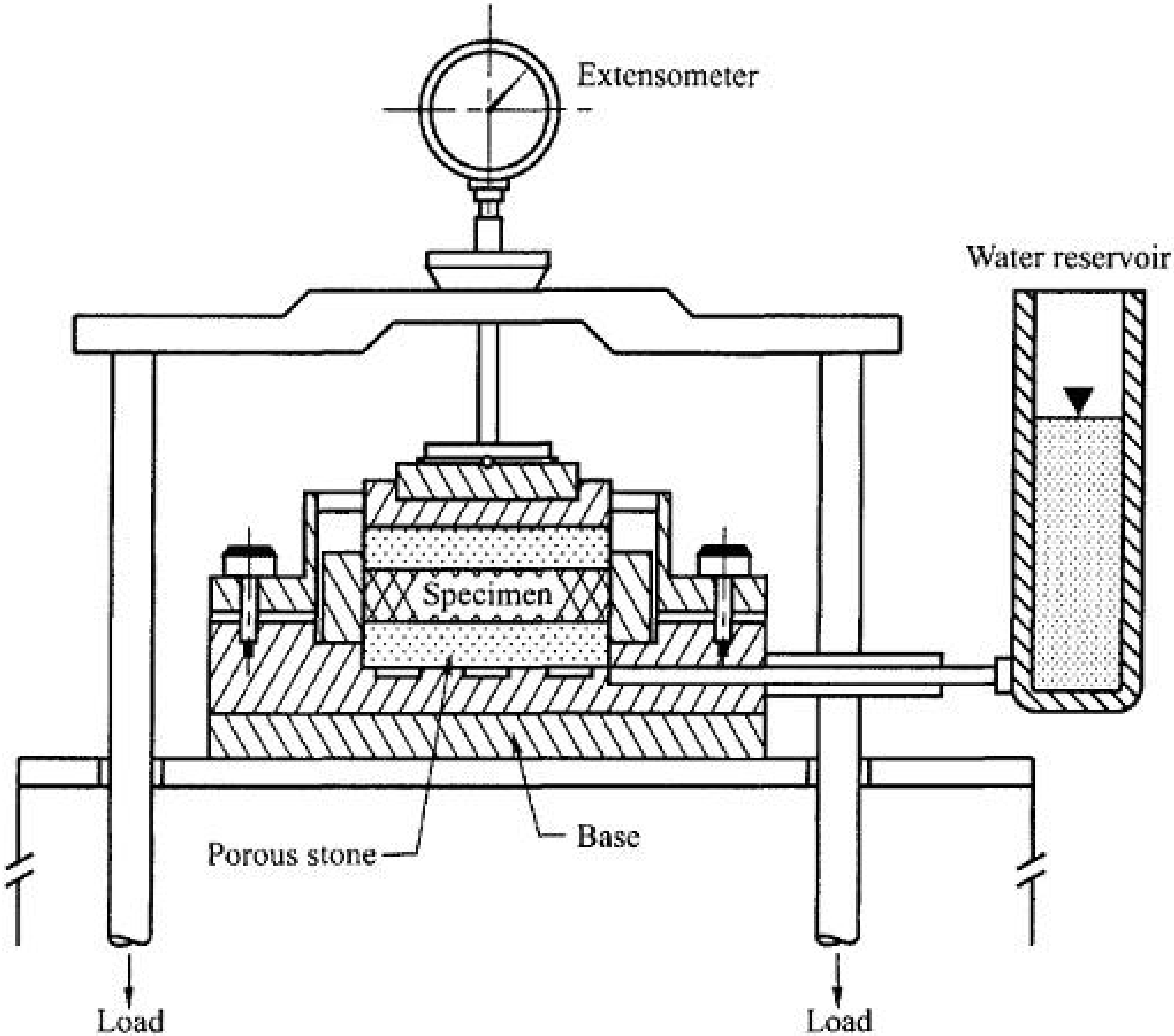
- The amount of settlement in the spring is depends on the stiffness of spring (compressibility characteristic of soil)
- The rate of settlement depends on the opening (permeability of soil)

Consolidation test

To determine the compressibility characteristics of soil one dimensional consolidation (Oedometer) test is carried out.

Objective of test:

1. To determine the amount of deformation
2. To determine the rate of deformation



Extensometer
Water reservoir
Specimen
Porous stone
Base
Load
Load

- Procedure:

1. Sample is placed in the cutting ring in between two porous stone.
2. The loading beam is then brought into contact and dial gauge is set at zero.
3. When first load of 10kN/m^2 is applied reading of dial gauge is taken at 1/4, ½, 1, 2, 4, 8, 16, 30, 60, 120, 240, 1440 mins.
4. Now load is doubled and dial gauge reading is taken as in *step 3.* Load is doubled upto 640kN/m^2
5. Unloading is done by removing 3/4th load and reading is observed as earlier.

Calculation

- Determination of void ratio

A. Height of solids method.

$$V_s = \frac{W}{G_s \gamma_w} \qquad e = \frac{Ah - Ah_s}{Ah_s} = \frac{h - h_s}{h_s}$$

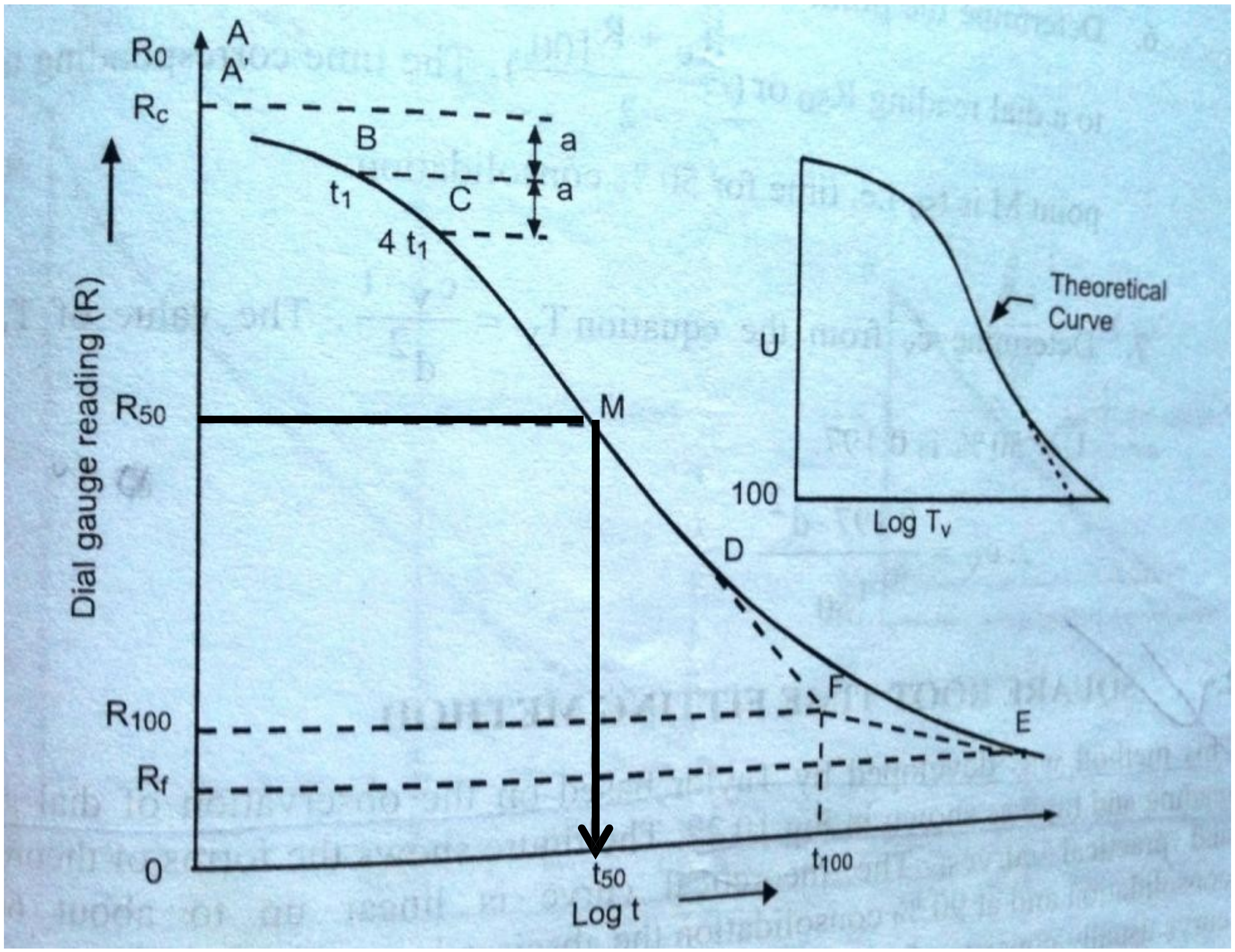
B. Change in void ratio method.

$$\frac{\Delta h}{h} = \frac{\Delta V}{V} = \frac{\Delta e}{1+e}$$

h= final height and, e= final void ratio

Determination of coefficient of consolidation

1. Logarithm of time : Casagrande method



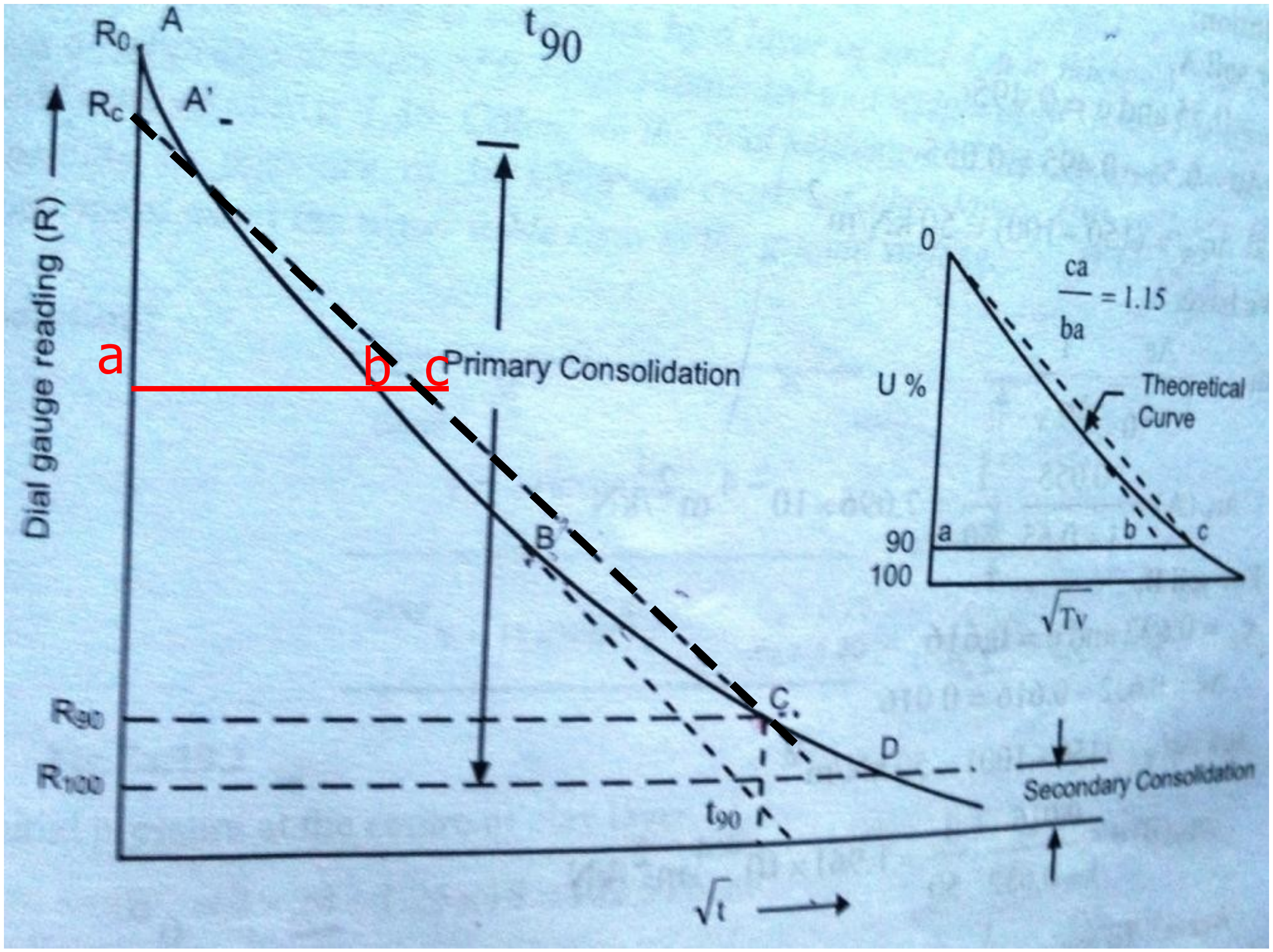
R50=(Rc+R100)/2

$T_v = (C_v\ t)/d^2$

$T_v = 0.197$

For 50% consolidation

2. Square root time: Taylor method



$T_v = (C_v\, t)/d^2$

$T_v = 0.848$

For 90% consolidation

Terzaghi theory of one dimensional consolidation

Assumptions

1.The soil is homogenous

2. The soil is fully saturated

3. The solid particles and water are incompressible

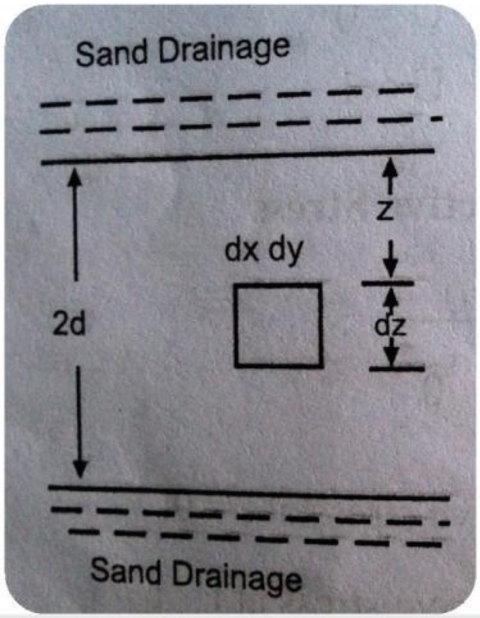
4. The flow is one dimensional

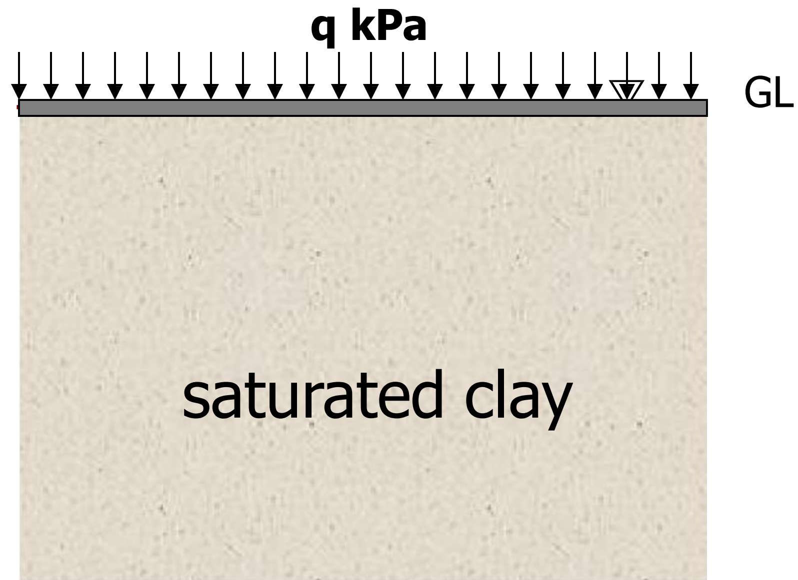
5. Darcy’s law is valid

6. k and m_v remains constant

7.There is unique relationship betn void ratio and effective stress and remain constant

One Dimensional Consolidation





According to Darcy's law

$$V_z = -k_z \times i$$

$$V_z = -k_z \times \frac{dh}{dz}$$

$$V_z = -k_z \times \left(\frac{\partial u}{\partial z}\right)\frac{1}{\gamma_w}$$

Inflow $= dx \times dy \times V_z$

Out flow =

$$dx \times dy \times \left(V_z + \frac{\partial V_z}{\partial z} \times dz\right)$$

Difference

$$dq = \frac{\partial V_z}{\partial z} \times dz \times dx \times dy$$

$$dq = \frac{dV}{dt} = \frac{\partial V_z}{\partial z} \times dz \times dx \times dy$$

or

$$\mathrm{dq} = \frac{\partial\left(-k_z \times \left(\frac{\partial u}{\partial z}\right)\frac{1}{\gamma_w}\right)}{\partial z} \times dz \times dx \times dy \text{--------}1$$

Now we know, $\frac{dV}{V} = m_v \times \Delta\sigma'_v$

Or, $dV = dx \times dy \times dz \times m_v \times \Delta\sigma'_v$

Or, $\mathrm{dq} = \frac{dV}{dt} = dx \times dy \times dz \times m_v \times \frac{\Delta\sigma'_v}{dt}$ -------2

$$\frac{\Delta\sigma'_v}{dt} = -\frac{du}{dt}$$

$$\frac{du}{dt} = \frac{k_z}{m_v \times \gamma_w} \times \frac{\partial^2 u}{\partial z^2} = c_v \times \frac{\partial^2 u}{\partial z^2} \text{..........}3$$

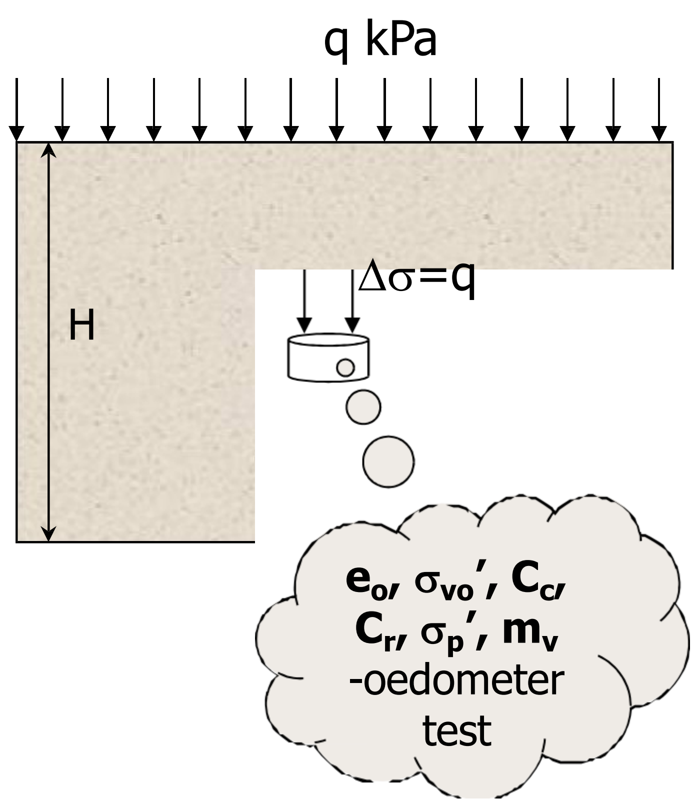
Solution of one-dimensional equation is complicated. The approximate solution used to calculated degree of consolidation

i. When U < 0.6 : $T_v = U^2 \frac{\pi}{4}$

ii. When U > 0.6 :

$$T_v = -0.933 \log(1 - U) - 0.085$$

Settlement computations



Two different ways to estimate the consolidation settlement:

(a) using m_v

$$\text{settlement} = m_v \, \Delta\sigma \, H$$

(b) using e-log σ_v' plot

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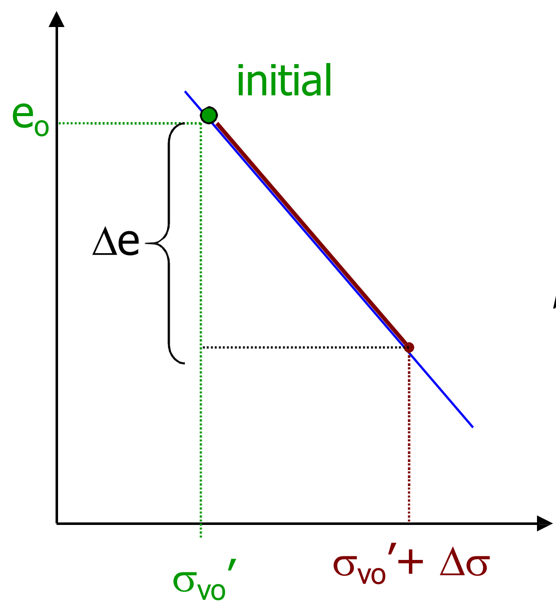
$$settlement = \frac{\Delta e}{1 + e_o} H$$

Settlement computations

~ computing Δe using e-log σ_v' plot

If the clay is normally consolidated,

the entire loading path is along the VCL.



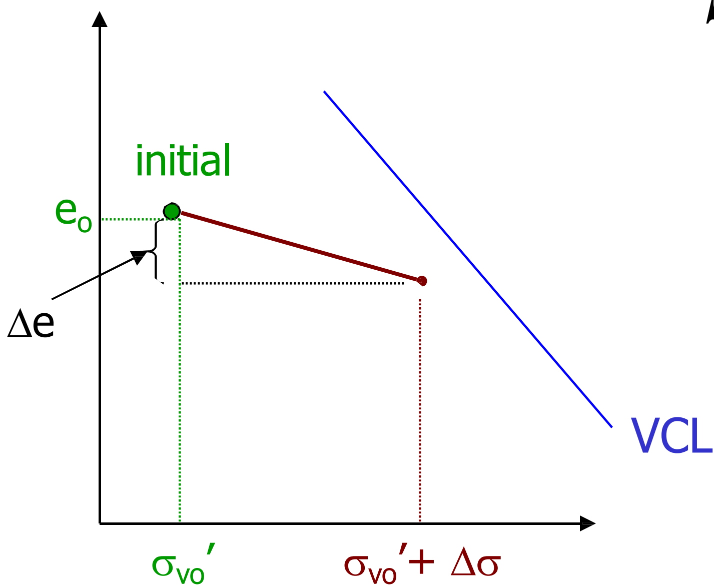
$$S = \frac{H}{1+e_0} C_c \log \frac{\sigma_{vo}' + \Delta\sigma'}{\sigma_{vo}'}$$

Settlement computations

~ computing Δe using e-log σ_v' plot

If the clay is <u>overconsolidated</u>, and remains so by the end of consolidation,

$$S = \frac{H}{1+e_0} C_r \log \frac{\sigma_{vo}' + \Delta\sigma'}{\sigma_{vo}'}$$



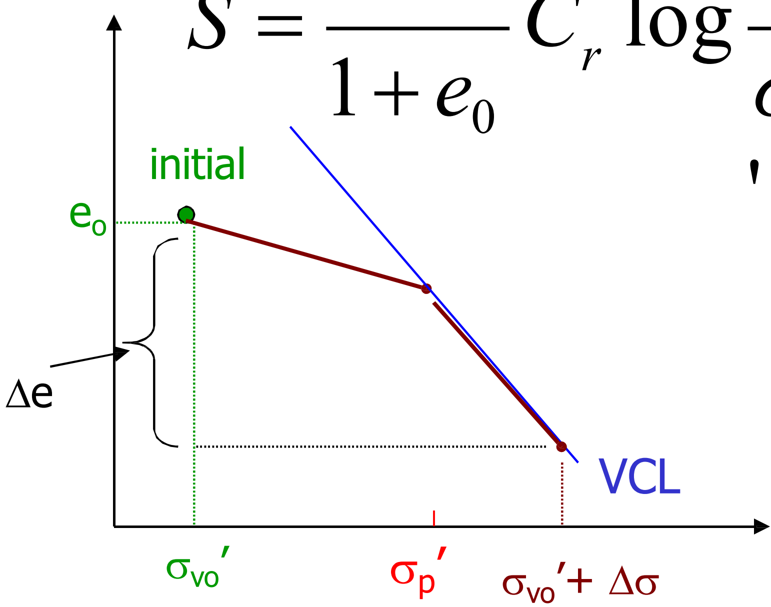
note the use of C_r

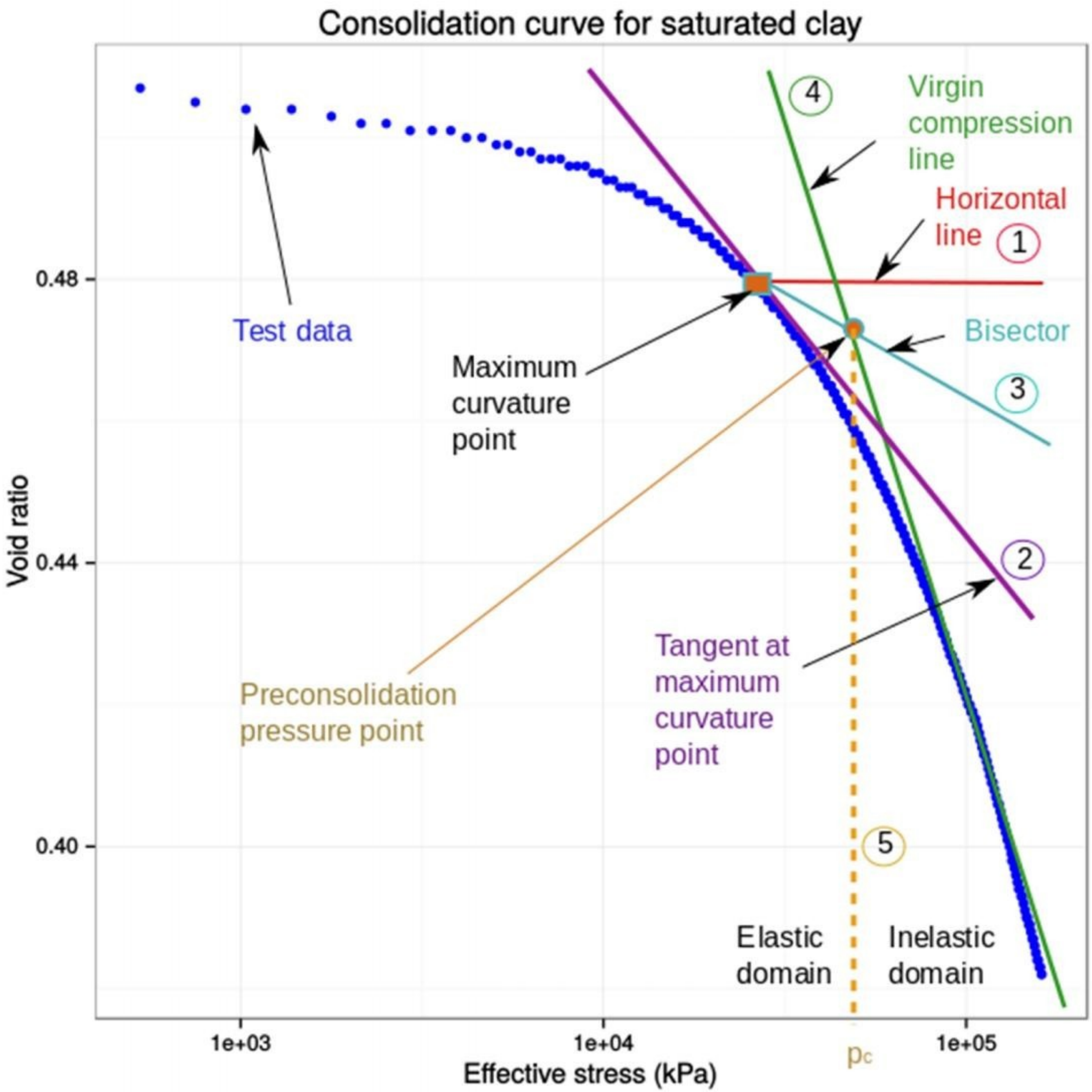
Settlement computations

~ computing Δe using e-log σ_v' plot

If an <u>overconsolidated</u> clay becomes normally consolidated by the end of consolidation,

$$S = \frac{H}{1+e_0} C_r \log \frac{\sigma_p'}{\sigma_{vo}'} + \frac{H}{1+e_0} C_c \log \frac{\sigma_{vo}' + \Delta\sigma}{\sigma_p'}$$





Consolidation curve for saturated clay
Void ratio
0.48
0.44
0.40
1e+03
1e+04
1e+05
Effective stress (kPa)
Test data
Virgin compression line
Horizontal line
Bisector
Maximum curvature point
Tangent at maximum curvature point
Preconsolidation pressure point
1
2
3
4
5
Elastic domain
Inelastic domain
pc