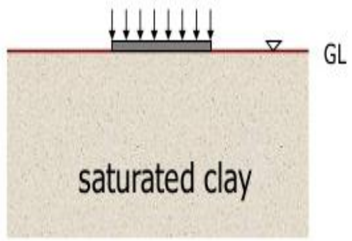
Chapter Three

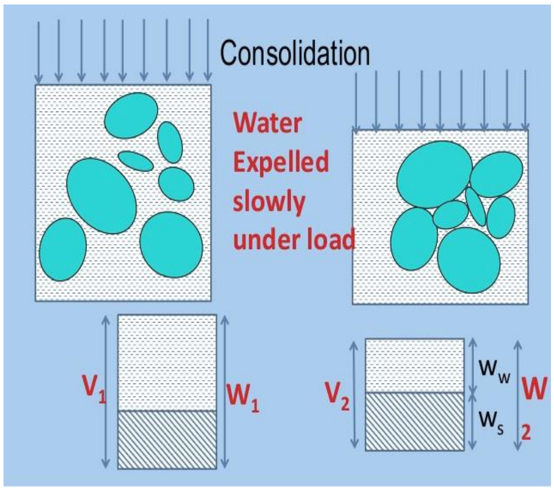
Consolidation

What is consolidation?

* When a saturated soil is loaded externally,

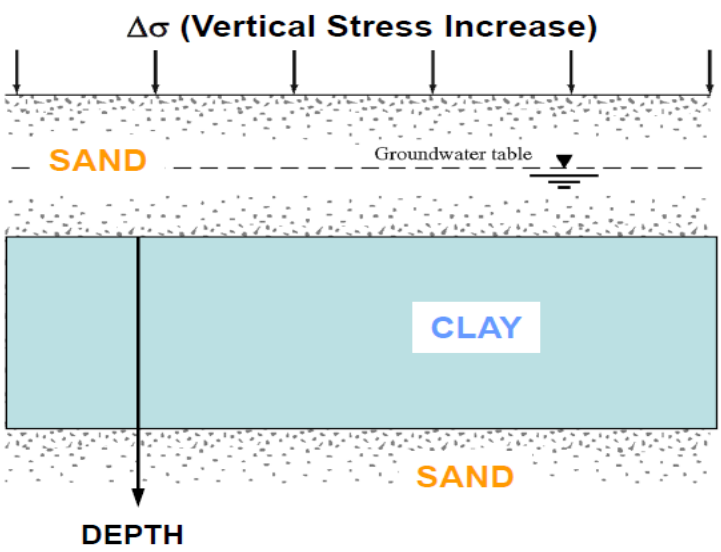


the water is squeezed out of the soil and the soil shrinks, over a long time may be up to several years depending upon the permeability of the soil this whole phenomena is called consolidation.



Fundamentals of Consolidation

Volume change in saturated soils caused by the expulsion of pore water from loading.
Saturated Soils: $\Delta\sigma$ causes *u* to increase immediately
Sands: Pore pressure increase dissipates rapidly due to high permeability.
Clays: Pore Pressure dissipates slowly due to low permeability.



Mechanics of Consolidation

- Spring Piston Model
- A cylindrical vessel with compartments marked by pistons separated by springs
- Pistons has perforations to allow water to flow through
- Piezometers inserted at middle of each compartment
- Space between springs filled with water.

- Apply pressure $\Delta\sigma$ on the top most piston.
- Immediately on application of load,
  - Length of springs remain unchanged
  - As a result, the entire $\Delta\sigma$ is borne by water in the vessel. Δu is the excess hydrostatic pressure
  - Initial rise in water level $h = \frac{\Delta\sigma}{\gamma_w}$

- After time t, flow of water through the perforations has begun at upper compartments. There is a corresponding decrease in volume, the upper springs have compressed a little.
- They carry portion of applied loads and a drop in pressure occurs. The isochrone for $t=t_1$ represents the pore distribution at upper and lower compartments.

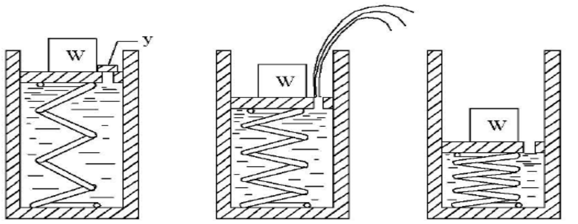
- The decrease in soil volume by the squeezing out of pore water on account of gradual dissipation of excess hydrostatic pressure induced by an imposed total stress is called consolidation.

Terzaghi's 1-D Theory of Consolidation

- A Theory to predict the pore pressures at any elapsed time and at any location is required to predict the time rate of consolidation of a consolidating layer.
- Assumptions:

1. Compression and flow is 1-D
2. Darcy's Law is valid
3. Soil is homogeneous and completely saturated
4. Soil grains and water are both incompressible
5. Strains are small. Applied del sigma produce virtually no changes in thickness,
6. k, av are constant.
7. No secondary compression.

THE SPRING ANALOGY



(a) Initial Loading

Water takes load

Soil (i.e. spring) has no load

(b) Dissipation of Excess Water Pressure

Water dissipating

Soil starts to

(c) Final Loading

Water dissipated

Soil has load

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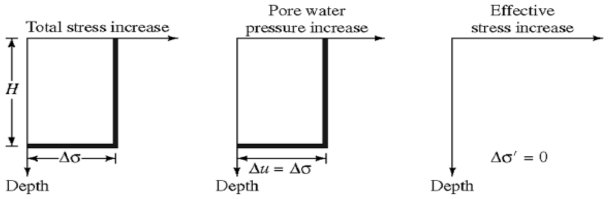
At Time of Initial Loading (t = 0)

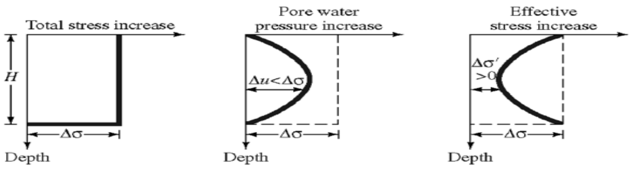


Variation in Total, Pore water, and Effective Stresses in Clay Layer
Figure 7.1b. Das FGE (2005)

Pore water takes initial change in vertical loading ($\Delta\sigma = \Delta u$) since water is incompressible

Soil skeleton does not see initial loading

Between time t = 0 to t = ∞

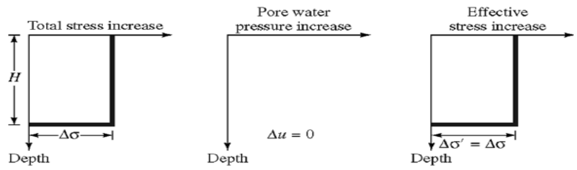


Variation in Total, Pore water, and Effective Stresses in Clay Layer
Figure 7.1c. Das FGE (2005)

Pore water increase due to initial loading dissipates

Soil skeleton takes loading as pore pressure decreases

At time t = ∞



Variation in Total, Pore water, and Effective Stresses in Clay Layer
Figure 7.1e. Das FGE (2005)

Pore water increase due to initial loading completely dissipated ($\Delta u = 0$)

Soil skeleton has taken loading. Effective stress increase now equals vertical stress increase ($\Delta\sigma = \Delta'\sigma$)

The excess hydrostatic pressure can be given as:

$$\Delta u = \frac{P}{A}$$

$$P = P_s + P_w$$

where P_s = load carried by the spring and P_w = load carried by the water.

when the valve is closed after the placement of the load P:

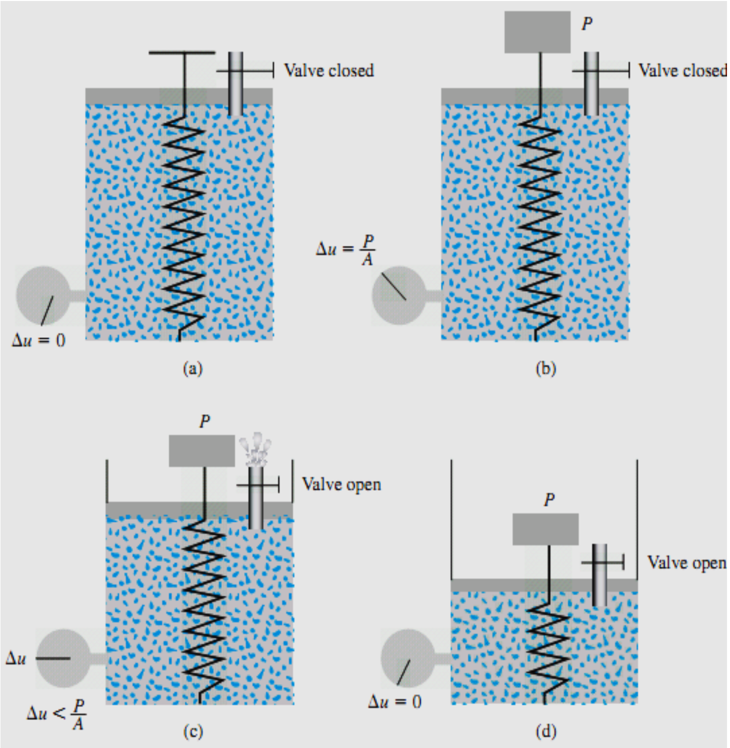
$$P_s = 0 \quad \text{and} \quad P_w = P$$

if the valve is opened:

$$P_s > 0 \quad \text{and} \quad P_w < P$$

After some time, the excess hydrostatic pressure will become zero and the system will reach a state of equilibrium:

$$P_s = P \quad \text{and} \quad P_w = 0$$



<u>One-Dimensional Consolidation Test</u>

- 1-D consolidation testing procedure was first suggested by Terzaghi.
- The main purpose of consolidation tests is to obtain data which is used in predicting the rate and amount of settlement of structures founded on clay.

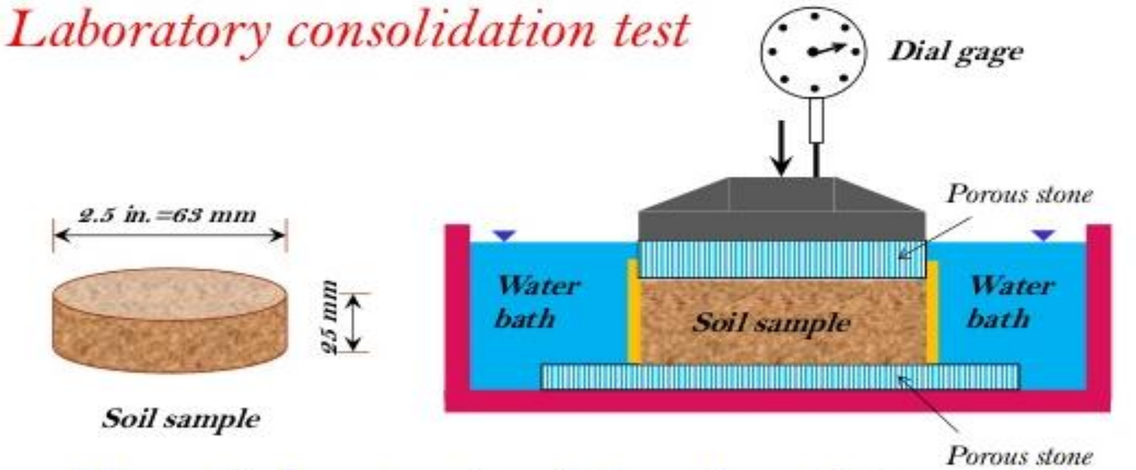
<u>The most important soil properties found by a consolidation test are:</u>

1. The pre-consolidation pressure ($\boldsymbol{\sigma c'}$) is the maximum stress that the soil had subjected to in the past;
2. The compression index (Cc) is the compressibility of a normally consolidated soil;
3. iii. The recompression index (Cr) is the compressibility of an over-consolidated soil;
4. iv. The coefficient of consolidation (Cv) is the rate of compression under a load increment.

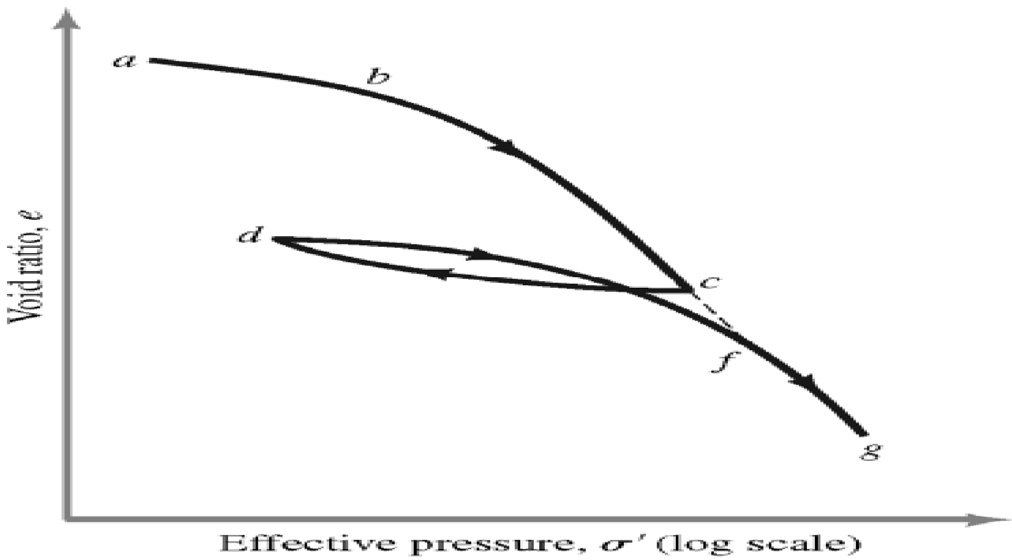
<u>Test Procedure</u>

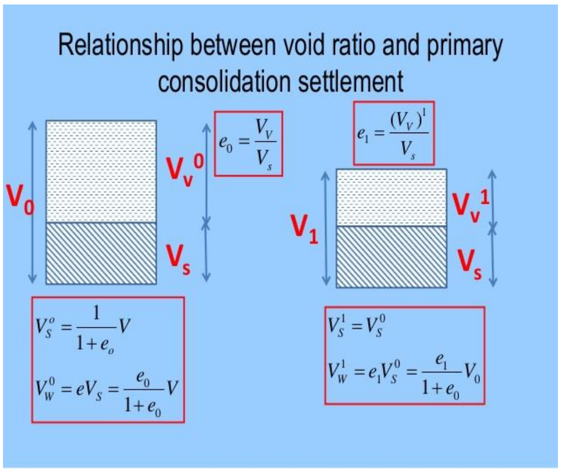
- The soil specimen is placed inside a metal ring with two porous stones, one at top of the specimen and another at bottom.
- The specimens are usually 75 mm in diameter and 19 mm thick.
- The load on the specimen is applied through a lever arm, and compression is measured by a dial gauge. The specimen is kept under water during the test.

- Each load usually is kept for 24 hours. After that, the load is doubled and the compression measurement is continued.
- At the end of the test, the dry weight of the test specimen is determined.



The vertical compression of the soil sample is recorded using highly accurate dial gauges.



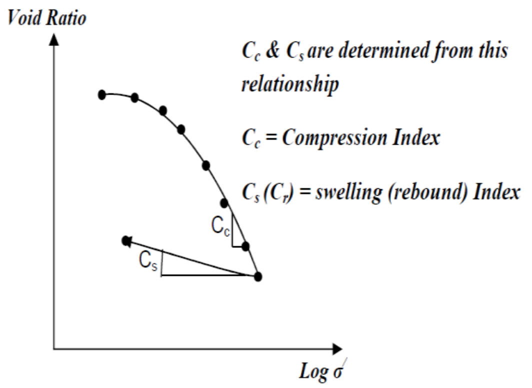


Relationship between void ratio and primary consolidation settlement

$$\Delta V = V_1 - V_0 = V_V^1 - V_V^0 = V_W^1 - V_W^0 = \frac{e_1 - e_0}{1+e_0}V = \frac{\Delta e}{1+e_0}V$$

$$\Delta V = \frac{\Delta e}{1+e_0}V$$

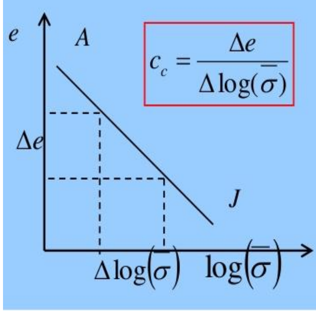
$$\Delta H = \frac{\Delta e}{1+e_0}H$$



Change in void ratio vs. vertical effective stress

Definitions

Compression Index

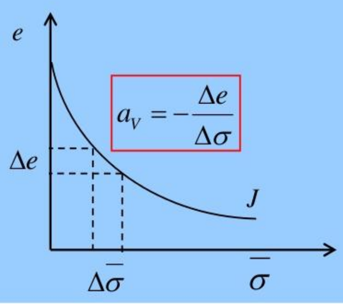


$$c_c = \frac{\Delta e}{\Delta \log(\bar{\sigma})}$$

$$c_c = \frac{e_2 - e_1}{\log\left(\frac{\bar{\sigma}_2}{\bar{\sigma}_1}\right)}$$

Definitions

Coefficient of Compressibility



$$a_V = -\frac{\Delta e}{\Delta \bar{\sigma}}$$

Definitions

Coefficient of Volume Compressibility

$$m_V = -\frac{\Delta V}{V} \Big/ \Delta \bar{\sigma}$$

$$m_V = -\frac{\Delta e}{1+e_0} \Big/ \Delta \bar{\sigma} = \frac{a_V}{1+e_0}$$

Compression Index (C_c) Estimates from Other Laboratory Tests

Soil	C_c Equation	Reference
Undisturbed Clays	$C_c = 0.009(LL-10)$	Terzaghi & Peck (1967)
Disturbed Clays	$C_c = 0.007(LL-10)$	
Organic Soils, Peat	$C_c = 0.0115W_n$	EM 1110-1-1904
Clays	$C_c = 1.15(e_o - 0.35)$	
	$C_c = 0.012W_n$	
	$C_c = 0.01(LL-13)$	
Varved Clays	$C_c = (1+e_o) - [0.1 + 0.006(W_n - 25)]$	
Uniform Silts	$C_c = 0.20$	

Compression Index (C_c) Estimates from Other Laboratory Tests

Soil	C_c Equation	Reference
Clays	$C_c = 0.141G_s^{1.2}\left(\frac{1+e_o}{G_s}\right)^{2.38}$	Rendon-Herrero (1983)
Clays	$C_c = 0.2343\left[\frac{LL}{100}\right]G_s$	Nagaraj & Murty (1985)

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Where:

G_s = Specific Gravity of Solids
LL = Liquid Limit (in %)
W_n = Natural Water Content
e_o = Initial Void Ratio