

***SOIL MECHANICS II***  
***CIVL 311***  
**COURSE NOTES**  
**2012**

***Module 1***  
***One-dimensional Consolidation of***  
***Fine-grained Soils***



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## **Topics Covered:**

### **GENERAL INTRODUCTION**

- Introduction
- Review of Basic concepts
- Review of Response of Soils to Shearing Forces

### **PART 1 – SOIL MECHANICS**

- Module 1: One-dimensional Consolidation of Fine-grained Soils
- Module 2: Stresses in Soil from Surface Loads
- Module 3: Response of soils to Shearing
- Module 4: Lateral Earth Pressures
- Module 5: Shallow Foundations

### **PART 2 – GEOTECHNICAL ENGINEERING DESIGN**

- Module 6: Site Characterization and Introduction to Geotechnical Design
- Module 7: Design of Shallow Foundations
- Module 8: Design of Deep Foundations
- Module 9: Design of Earth Retaining Structures

## **Text Books:**

- Selected Chapters from Budhu: Soil Mechanics and Foundation, 2nd Edition and from Foundations and Earth Retaining Structures, 1st Edition, By M. Budhu, John Wiley & Sons. (CUSTOM PRINT)
- "Soil Testing for Engineers", T.W. Lambe, BiTech Publishers, Vancouver (originally published by John Wiley & Sons, 1951).

# Geotechnical Engineering:

## Civil Engineering embraces:

- Analysis
- Design
- Construction & Maintenance of a variety of structures & systems

## Different disciplines:

- Environmental
- **Geotechnical**
- Hydrotechnical
- Materials
- Structures
- Transportation
- Construction

- **Geotechnical Engineering:**

*“The application of the sciences of soil and rock mechanics, engineering geology and other related disciplines to civil engineering, the extractive industries and the preservation of the environment.” – Ground Engineering (November, 1999).*

- Its practice requires knowledge, understanding and appreciation of:
  - Engineering geology
  - Material science & testing
  - Mechanics (both Solid mechanics & Fluid mechanics)

# Impetus

**Civil engineering works are typically :**

- **supported on-land (near-surface);**
- **Installed below-ground; or**
- **made of earth material**

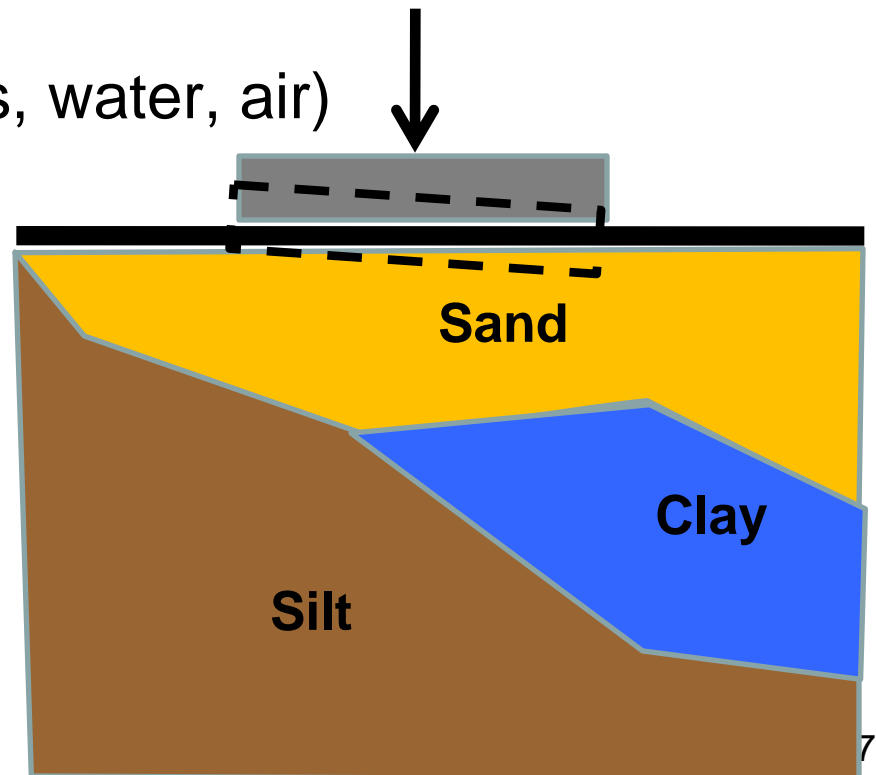
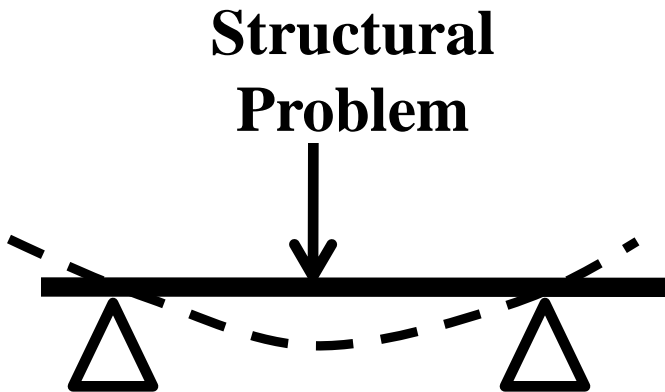
**→ Geotechnical Engineering  
has a major role to play**

# Problems involve the reducing the risk of the following to acceptable levels:

- Unacceptable settlements
  - compressibility
- Failure (collapse)
  - Shear strength properties
  - deformation modulus
- Control of seepage
  - permeability

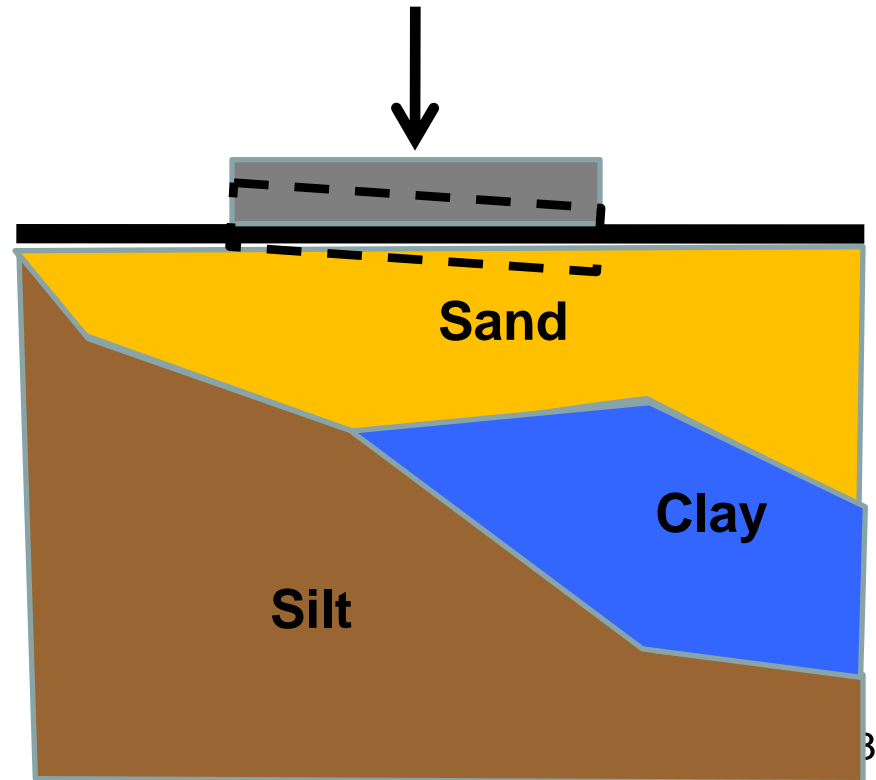
# General Problem

- Applied Loads  $\rightarrow$  Estimate Performance (Predict Deformations)
- Need to Understand Material Behaviour
- Soil Materials
  - Particulate
  - Three-phase (typ. solids, water, air)



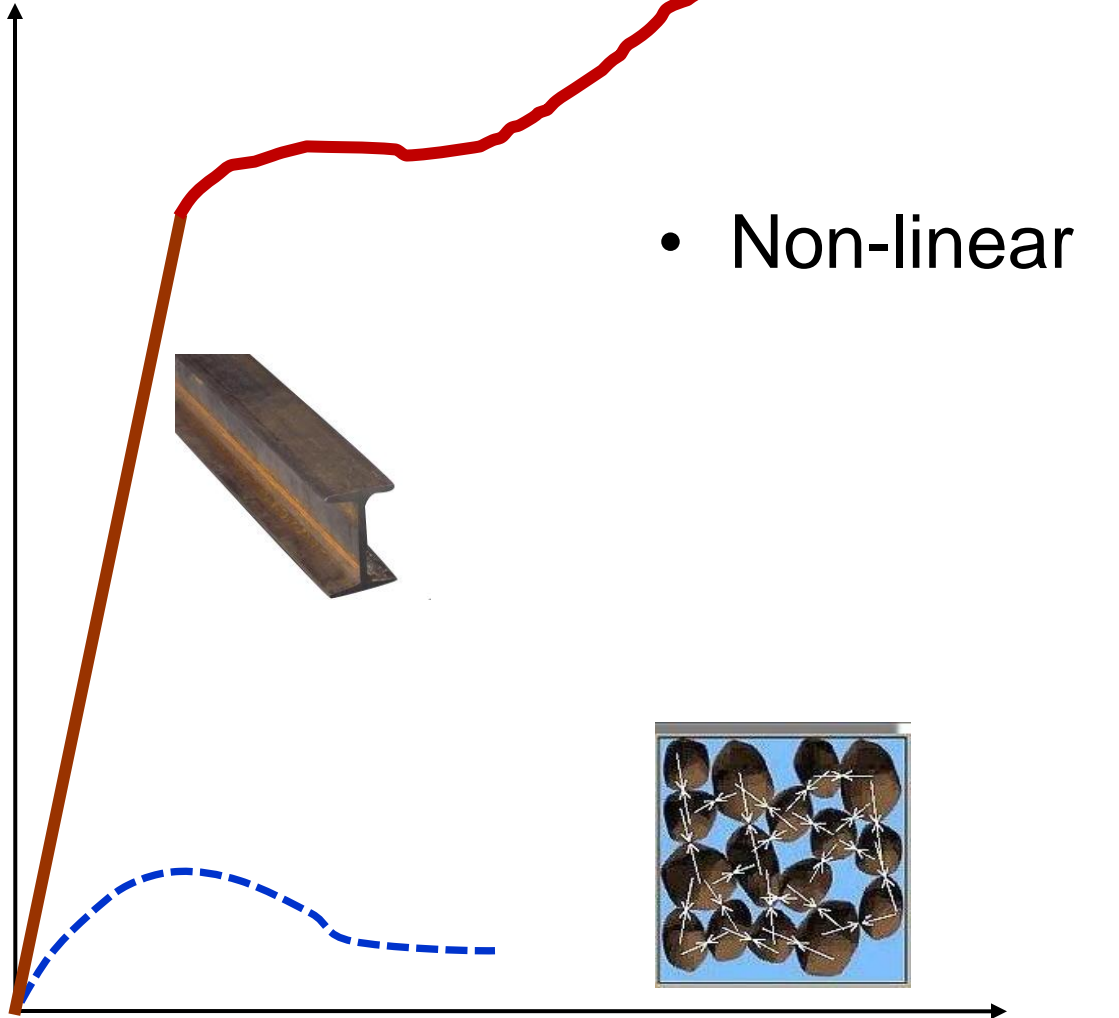
# Soil Behaviour

- dependent on effective stress  
pore water pressure  
– a critical consideration.



# Soil Behavior

Stress

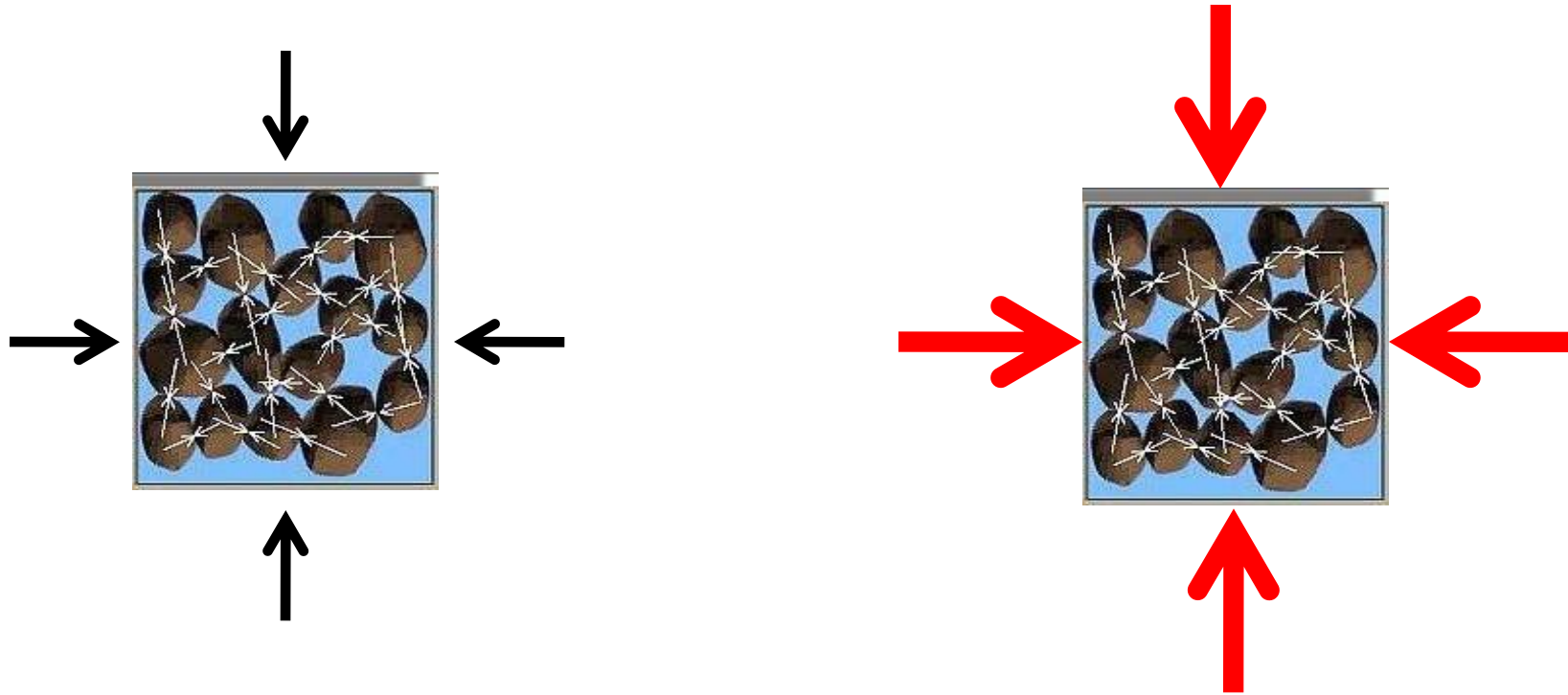


- Non-linear

Not to Scale

Strain

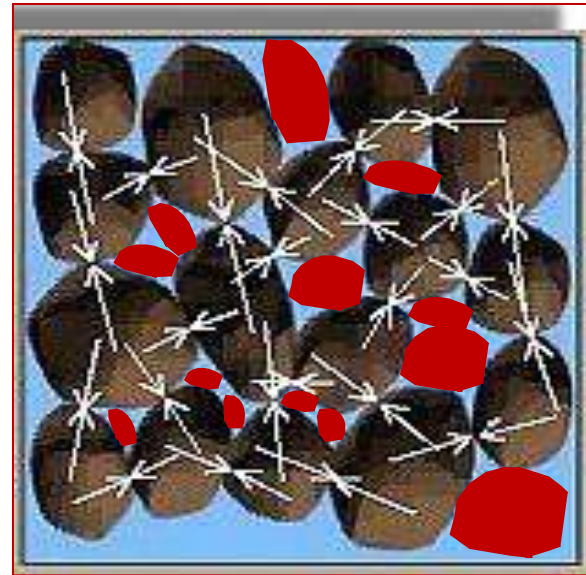
# Soil Behaviour



- governed by confining stress

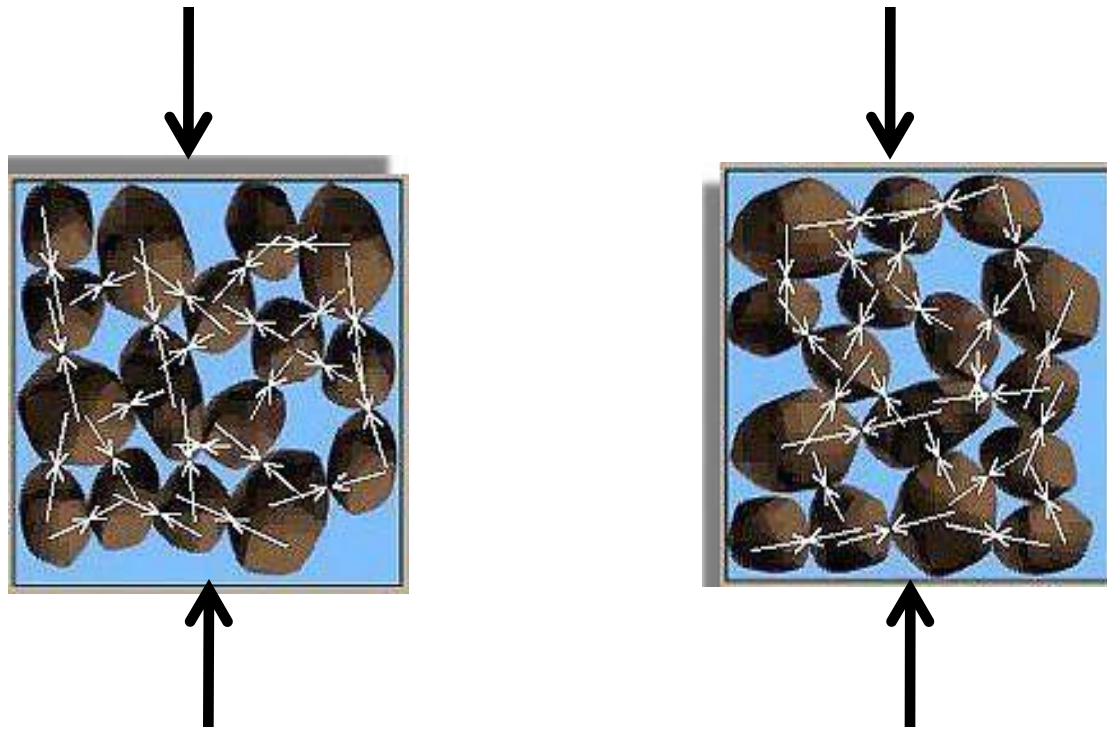
Examine soil behaviour using continuum mechanics principles

# Soil Behaviour



- governed by density  
(of particle packing)

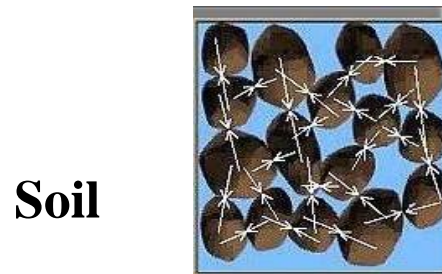
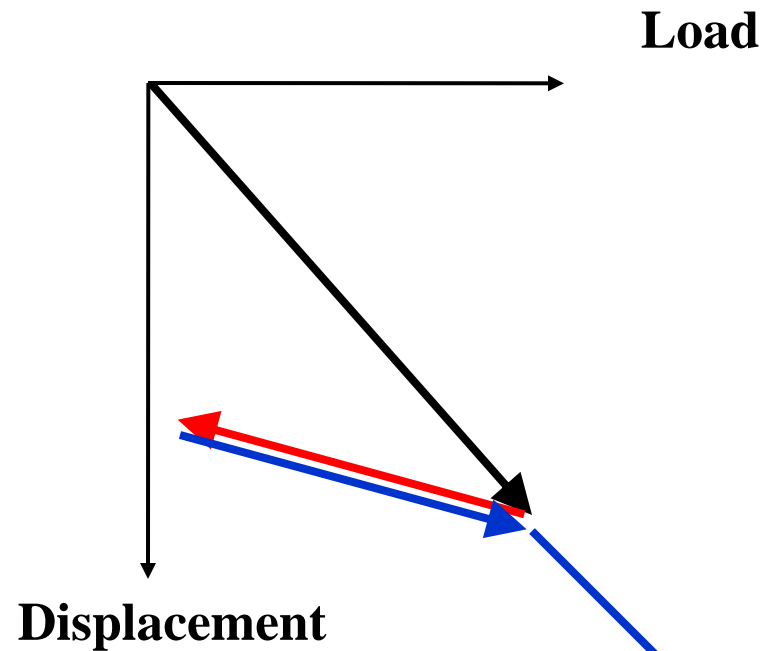
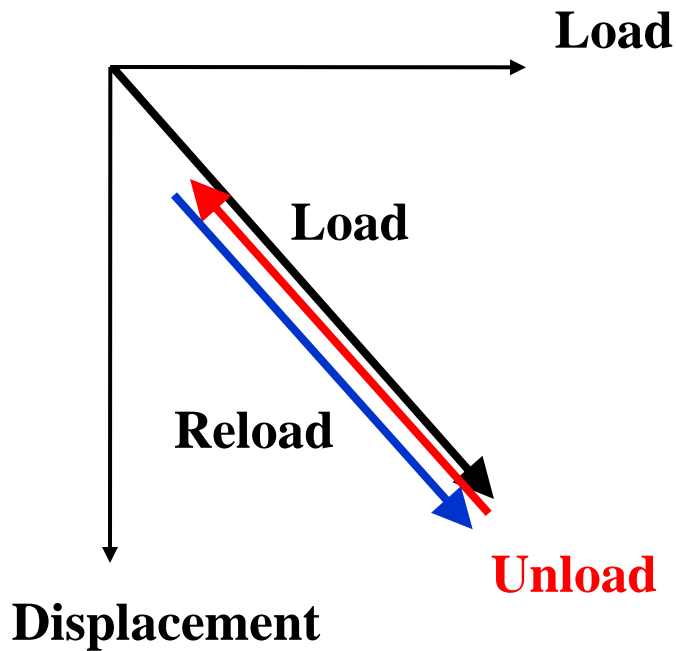
# Soil Behaviour



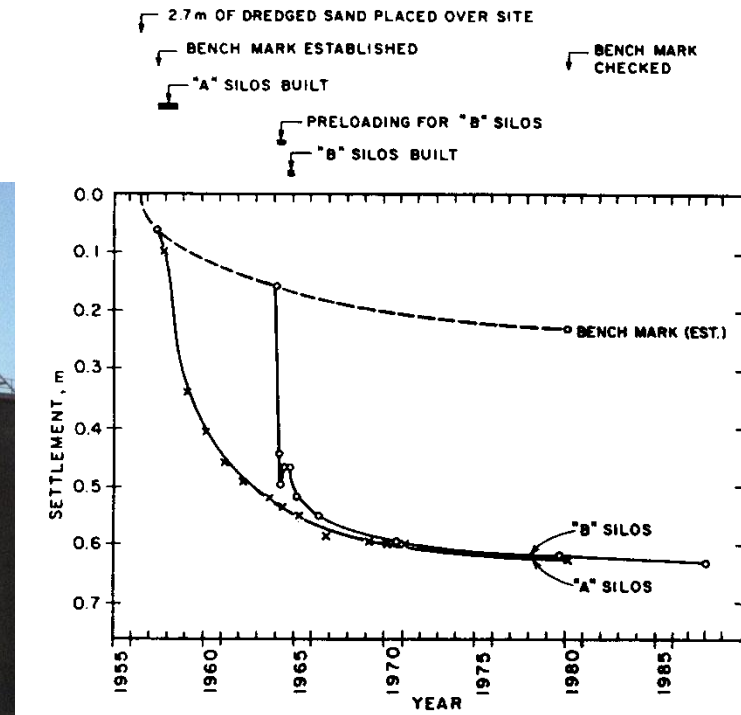
- governed by particle fabric (particle arrangement)

# Soil Behaviour

- loading “memory”



# Settlement of Structures



Ref: Crawford et al.  
(1991)  
Can. Geotech.  
Journal No. 28

Lafarge Cement Plant – Richmond BC

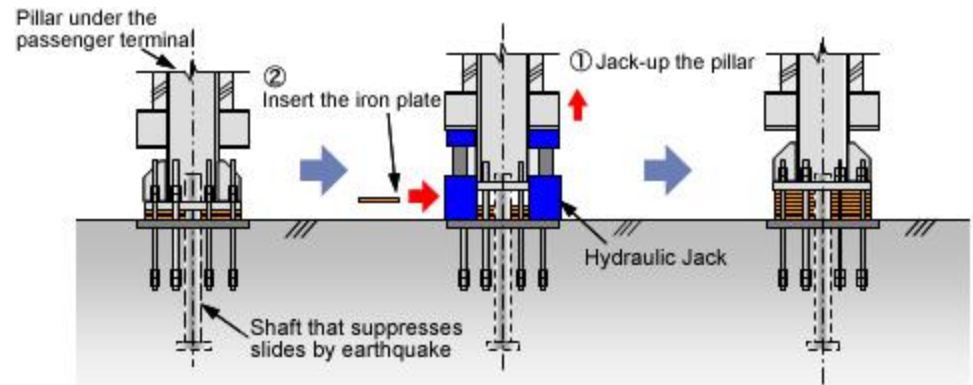
# Kansai International Airport



Built on soft clay in Osaka Bay, Japan

Island sank 8m, which was exceeded the original estimations

# Kansai International Airport



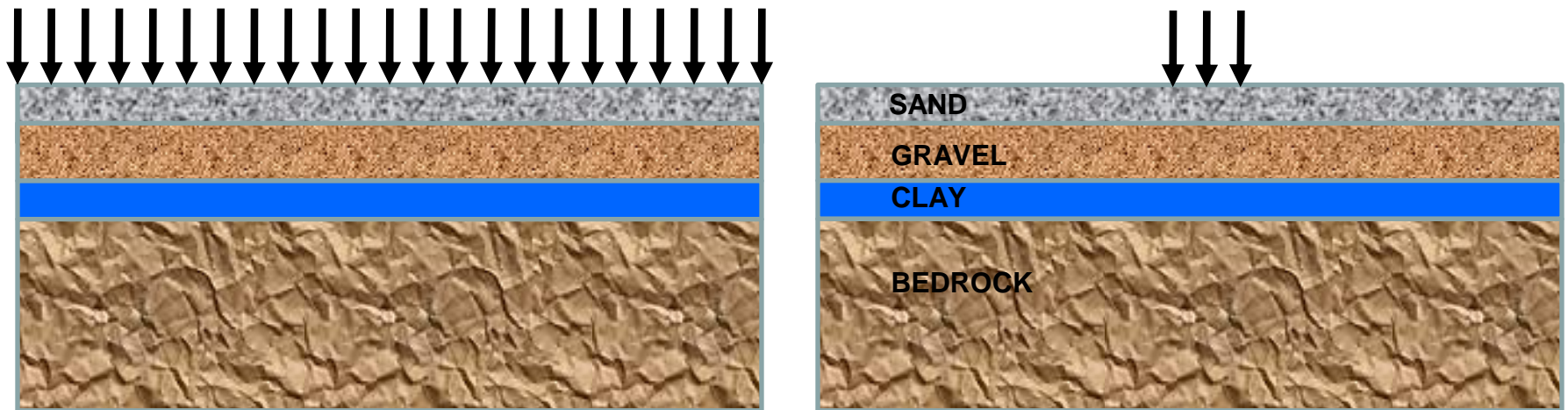
# **One-dimensional Consolidation of Fine-grained Soils**

## ***Overall Learning Objectives***

- Settlement of structures founded on, or constructed using, soils.
- General approach to computation of settlements.
- Common processes producing settlements (Primary/secondary compression, distortion)
- Terzaghi one-dimensional consolidation theory
- Settlement analysis (Rates of consolidation and secondary settlement, Ultimate settlement)
- Methods for reducing settlements

# One-dimensional Consolidation of Fine-grained Soils

- In many field problems, the soil mass is usually constrained laterally (on sides), thus the consolidation occurs only in vertical direction (i.e., one-dimensional)



# Common processes producing settlements

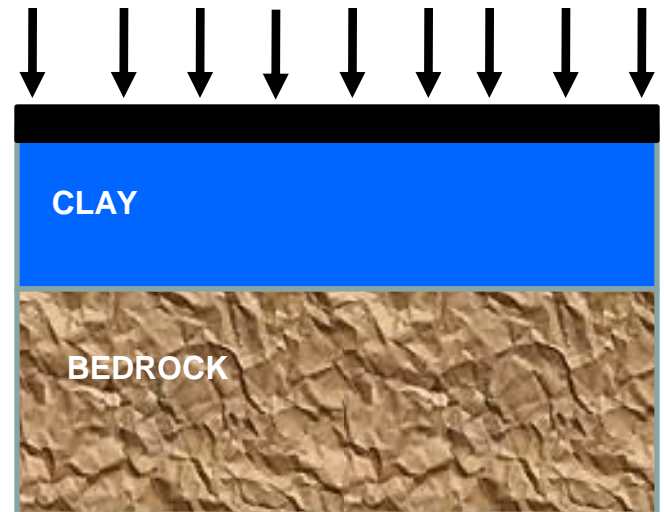
- (a) Distortion (immediate settlement)
- (b) Consolidation;
- (c) Secondary compression



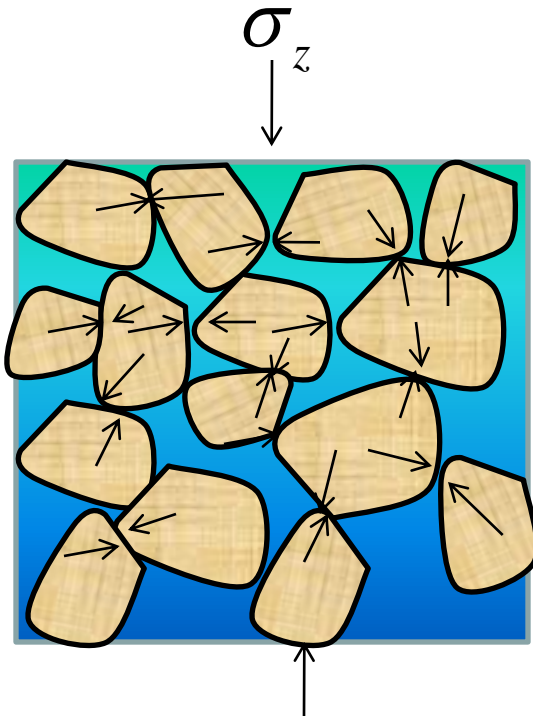
→ Main focus herein is on item (b)

→ Items (a) and (c) will be addressed as a separate item.

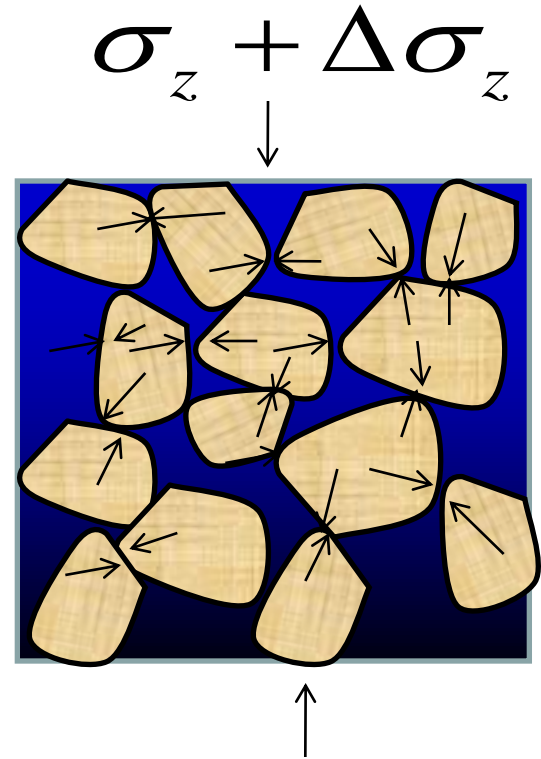
- **Immediate settlement**
  - No volume change (undrained)
  - Distortional
- **Primary Consolidation**
  - Excess water pressure dissipates (water drains out)
  - Effective stress increases
  - Soil skeleton volume decreases
  - Time dependent
- **Secondary compression**
  - Creep
  - Constant effective stress
  - Skeleton volume decreases
  - Fabric changes
  - Time dependent



# Stresses in soils



$$\sigma = \sigma' + u$$



$$\sigma_z \rightarrow \sigma_z + \Delta\sigma_z$$

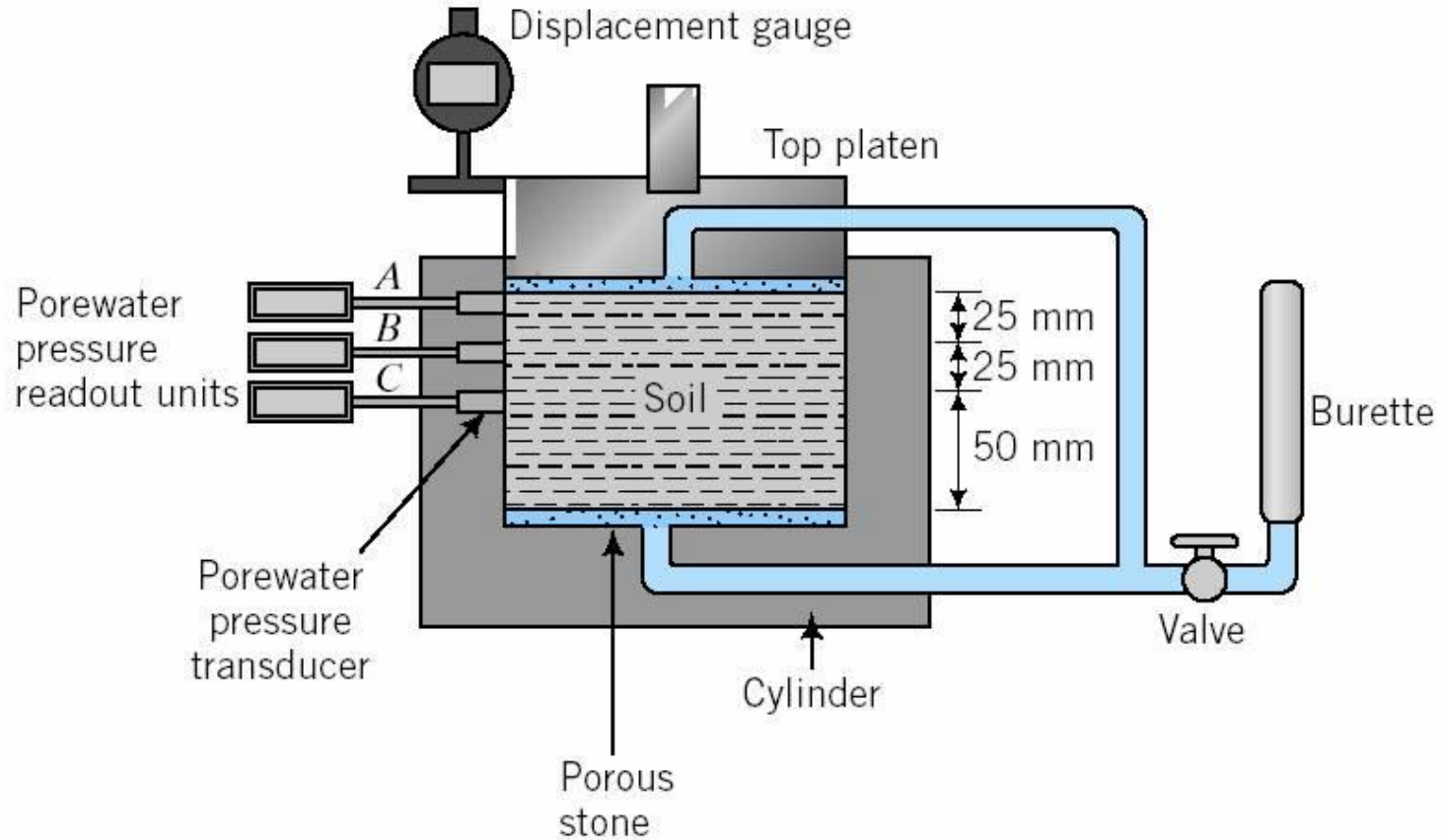
$$\therefore u \rightarrow u + \Delta u$$

$$\Delta\sigma_z = \Delta u$$

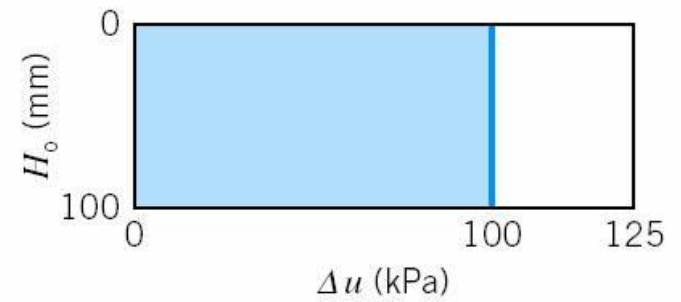
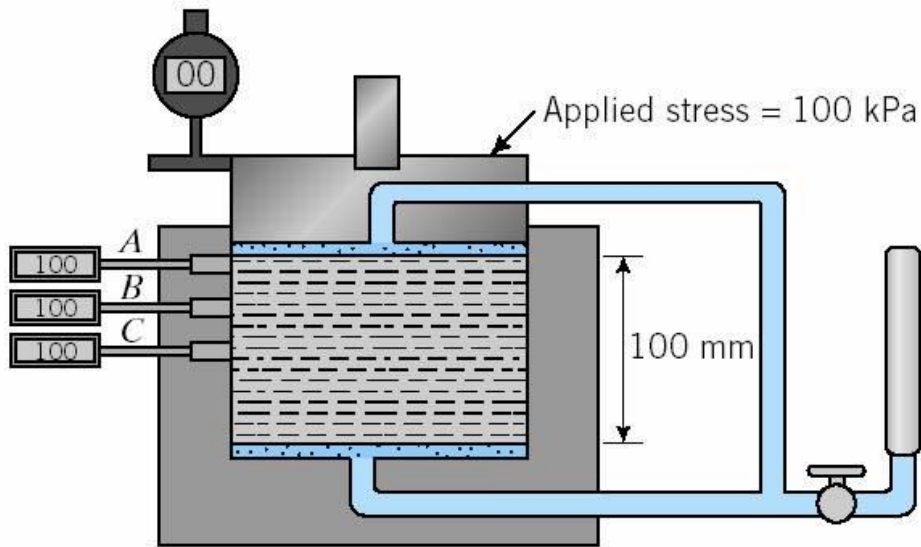
Assume no volume change

$\Delta u$  = excess pore water pressure

# Basic concepts of consolidation

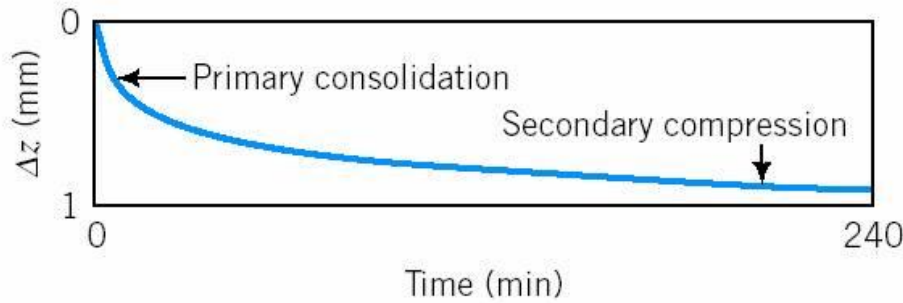
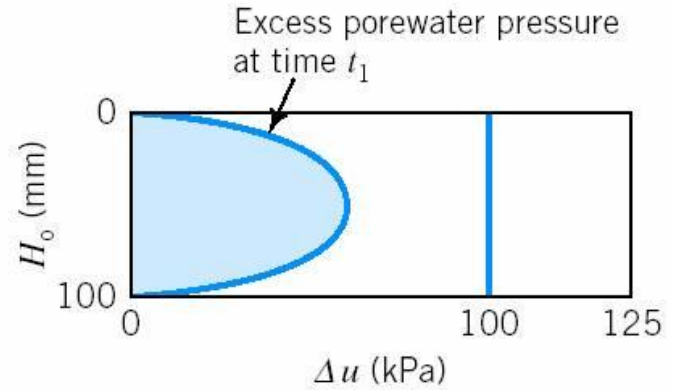
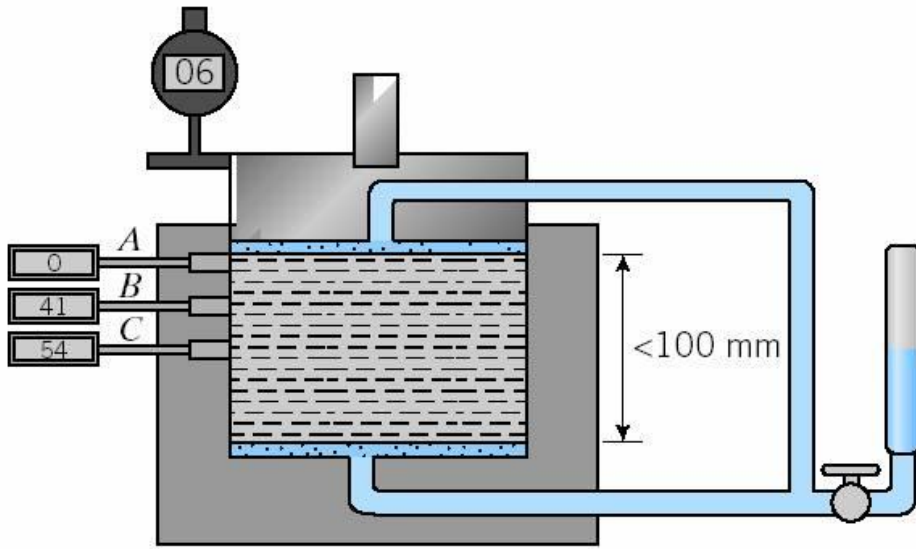


**Budhu Book 1 - Fig. 6.2a – Page 169**  
**Consolidation Test set up- Before application of load**



$$\Delta\sigma_z = \Delta u = 100 \text{ kPa}$$

Budhu book- Fig 6.2b- Immediately after application of load (100 kPa)



$H_0$  = height of soil (mm)  
 $\Delta z$  = change in height (mm)  
 $\Delta u$  = change in excess porewater pressure (kPa)

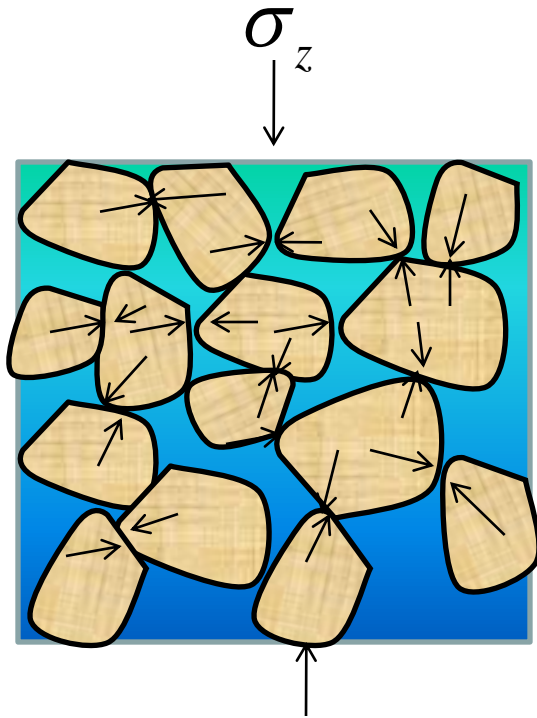
$$\Delta u < 100 \text{ kPa}$$

$$\Delta \sigma_z' > 0$$

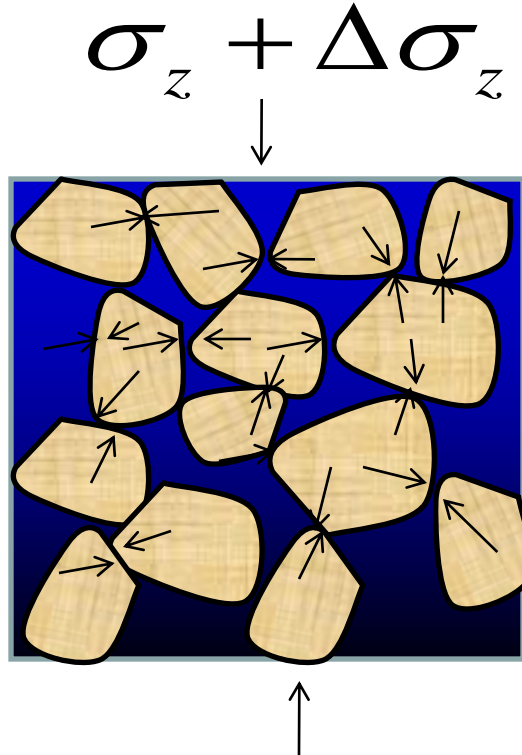
$$\Delta z > 0$$

Budhu book- Fig 6.2c- Some time after application of load (100 kPa)

# Stresses in soils



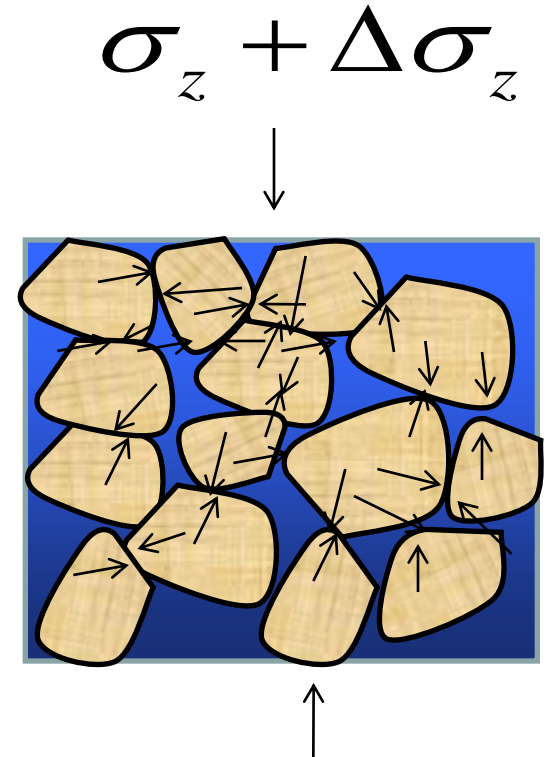
Before applying  $\Delta\sigma_z$



Immediately after applying  $\Delta\sigma_z$

$$\Delta\sigma_z = \Delta u$$

$$\Delta\sigma_z' = 0$$



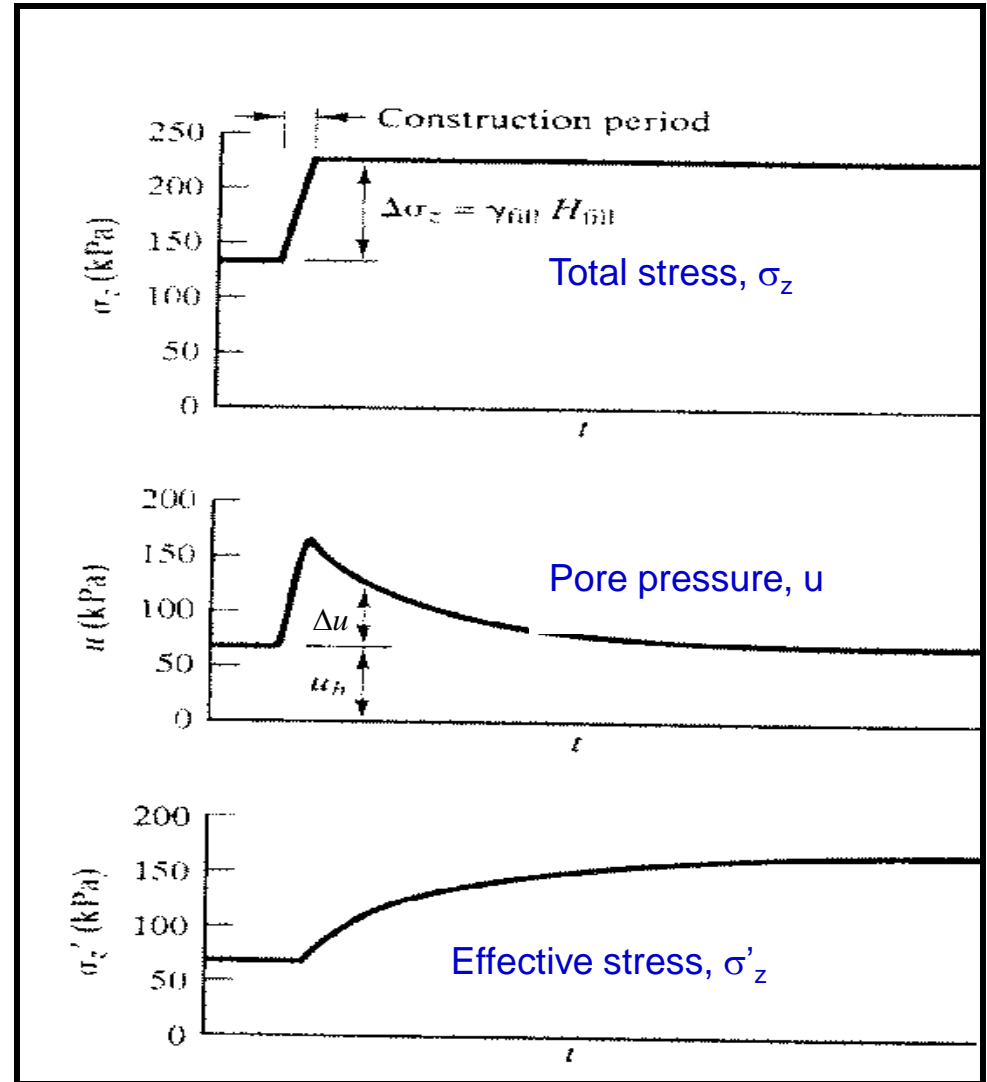
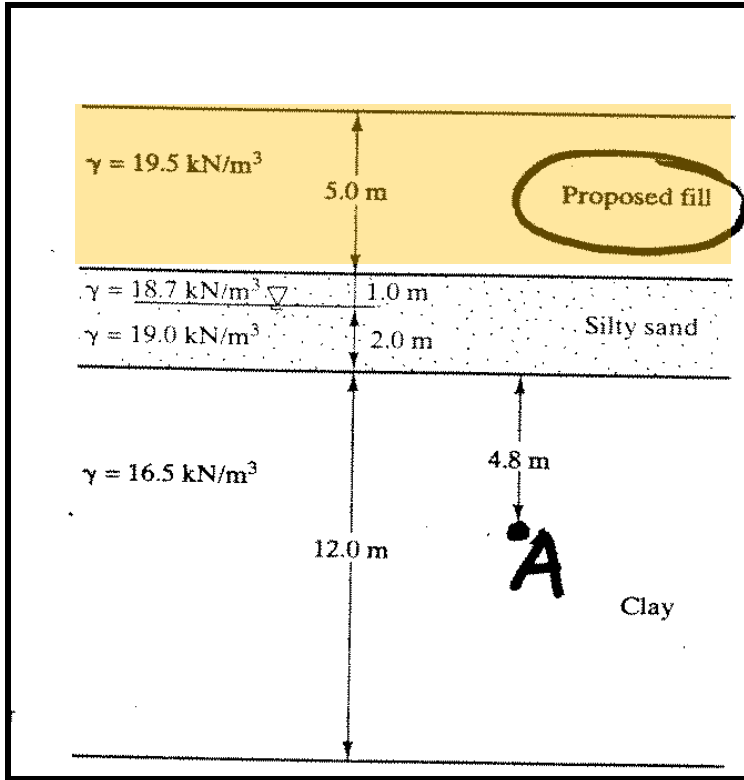
After time  $t$ :

$$\Delta u < \Delta\sigma_z$$

$$\Delta\sigma_z' > 0$$

$$\Delta z > 0$$

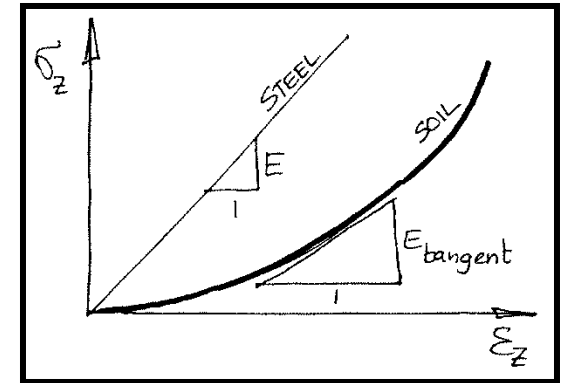
# Field response to loading



# General Approach to Computation of Settlements

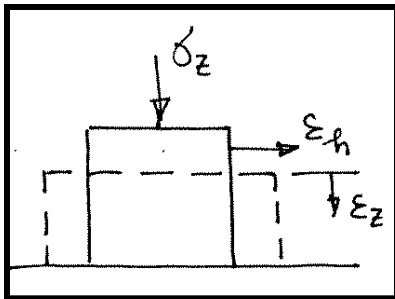
⇒ Steel – typically assumed linear

$$\varepsilon_z = \frac{1}{E} \sigma_z$$



⇒ Soils Nonlinear no single E, ν

$$d\varepsilon_z = \frac{1}{E_{\text{tangent}}} d\sigma_z$$



	E (MPa)	ν
Steel	200 x 10 <sup>3</sup>	0.15 (0.2)
Concrete	27 x 10 <sup>3</sup>	0.15 (0.2)
Soil	?	?

# Calculation of consolidation settlement

$$\varepsilon_z = \frac{\text{Change in height of sample}}{\text{Initial height of sample}} = \frac{\Delta z}{H_o}$$



$$\varepsilon_z = \frac{\Delta z}{H_o} = \frac{\Delta z * A}{H_o * A} = \frac{\Delta V_T}{V_T}$$

Vv = Volume of voids

Vs = Volume of soil

V<sub>T</sub> = Vv + Vs = Total volume

A = Cross-sectional area

$$\Delta V_T = \Delta V_V \quad \text{and} \quad V_T = V_V + V_S$$

$$\varepsilon_z = \frac{\Delta z}{H_o} = \frac{\Delta z * A}{H_o * A} = \frac{\Delta V_T}{V_T} = \frac{\Delta V_V}{V_V + V_S}$$

# Calculation of consolidation settlement

$$\frac{\Delta z}{H_o} = \frac{\Delta V_v / V_s}{(V_s + V_v) / V_s} = \frac{\Delta e}{1 + e_o}$$



Vv = Volume of voids

Vs = Volume of soil

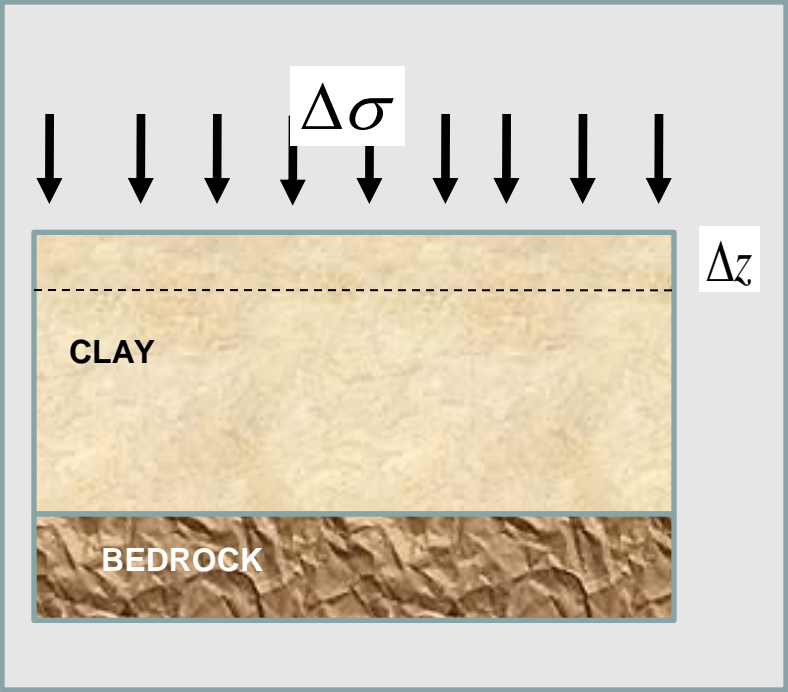
$V_T = V_v + V_s =$  Total volume

$$\varepsilon_z = \frac{\Delta z}{H_o} = \frac{\Delta e}{1 + e_o}$$

$$e = \frac{V_v}{V_s}$$



# Relationship between consolidation settlement and change in vertical pressure



$\Delta z$

$$\frac{\Delta z}{H_o} = \frac{\Delta e}{1 + e_o}$$

$\Delta e$

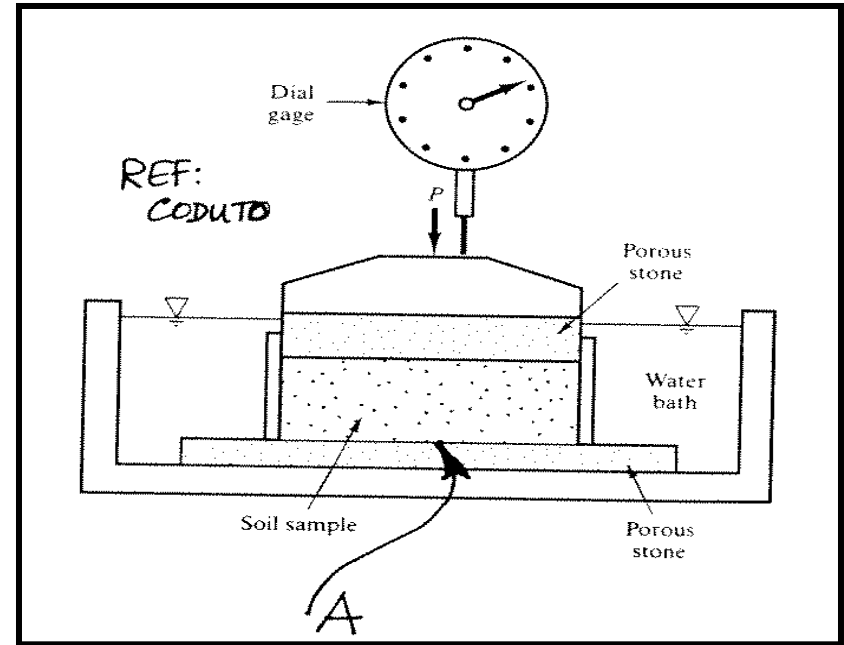
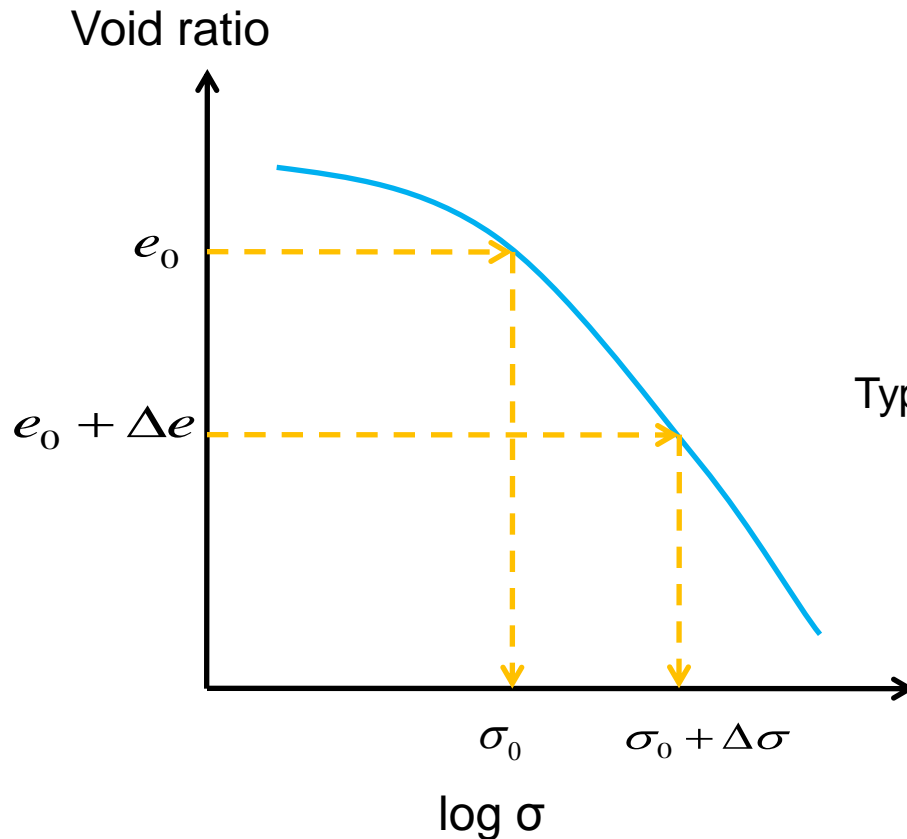
e-log  $\sigma$  curve

From consolidation test

$\Delta\sigma$

# e- log $\sigma$ relationship

e- log  $\sigma$  curve can be obtained from 1D consolidation test performed on a soil sample



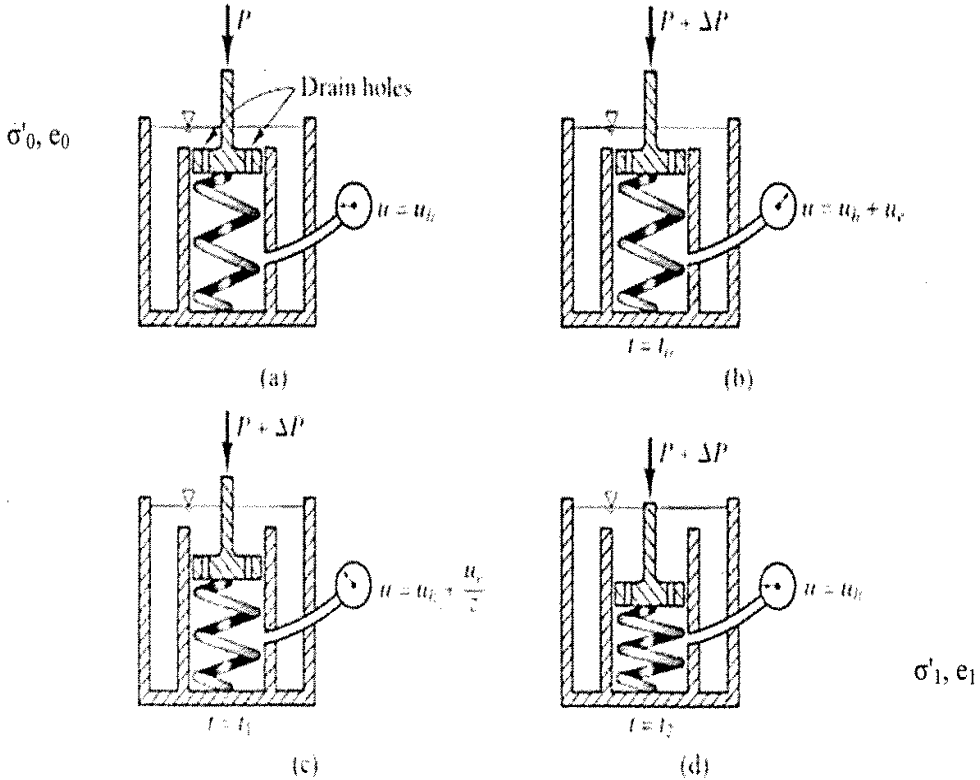
Typically: 5 to 8cm dia and 2 to 3cm thick specimen of soil

- Load increments applied every 24 hours
- Load doubled every time

# Consolidation Settlements

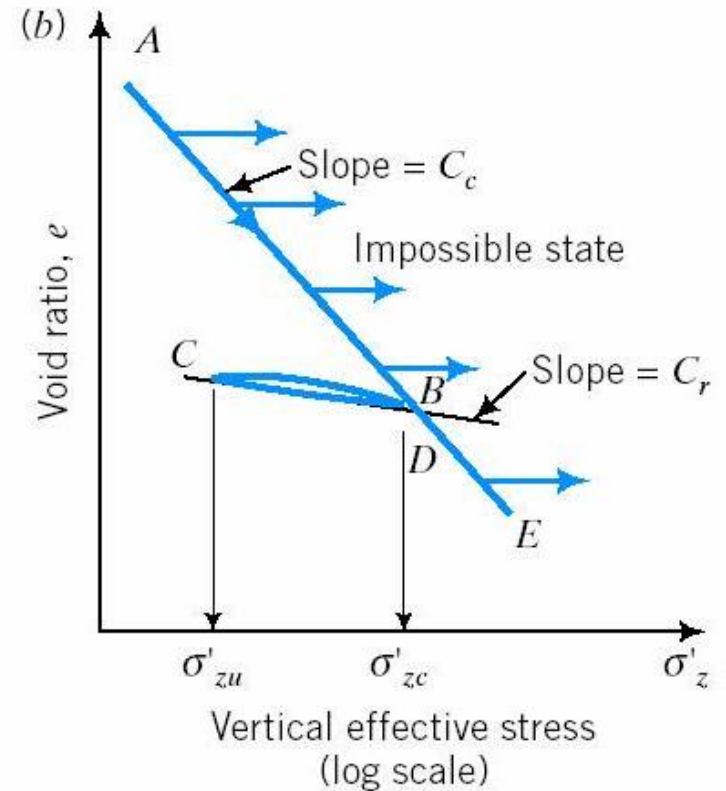
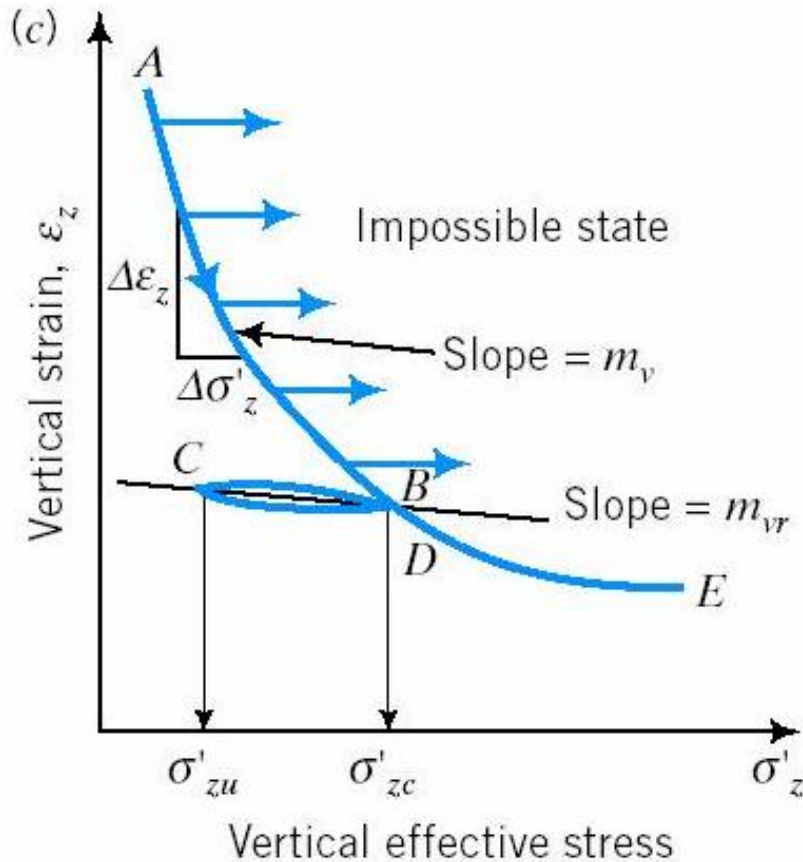
- Applied load at time  $t = 0$  is resisted solely by the pore water  $\rightarrow$  excess pore water pressure  $\Delta u = \Delta \sigma_z$  at  $t = 0$
- then  $\Delta u$  drops until  $\Delta u = 0 \rightarrow$  time dependent phenomenon, increasing  $t$  (rate of change in  $\Delta u$  is also governed by hydraulic conductivity  $k$ )
- In the process, stress transfer occurs from water to soil skeleton  $\rightarrow \sigma'_{fin} = \sigma'_{z0} + \Delta \sigma_z$
- Need to predict both the magnitude and rate of settlement

# Mechanical Analogy of Consolidation Process



<u>Soil</u>	<u>Analogy</u>
Soil skeleton	⊠ Spring, its stiffness corresponds to soil compressibility
Pore water pressure (u)	⊠ Water in piston
Drainage conditions	⊠ Valve (on drain holes)
Permeability (k)	⊠ Size of drain holes

# Consolidation test results (Ref: Budhu)

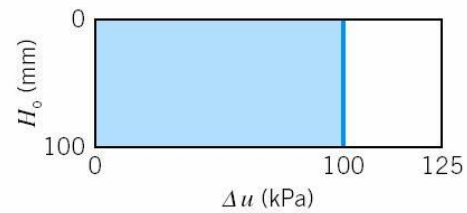
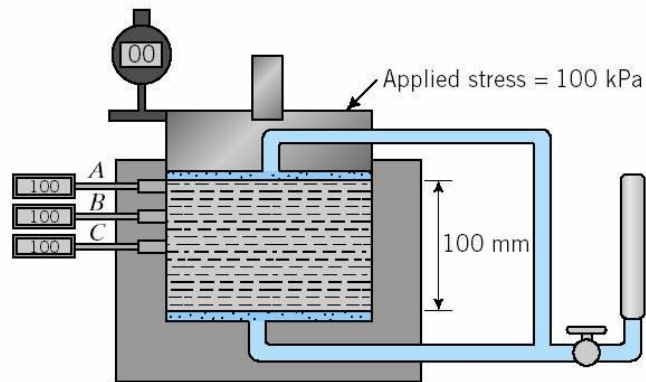


$$\varepsilon_z = \frac{\Delta H}{H_0}$$

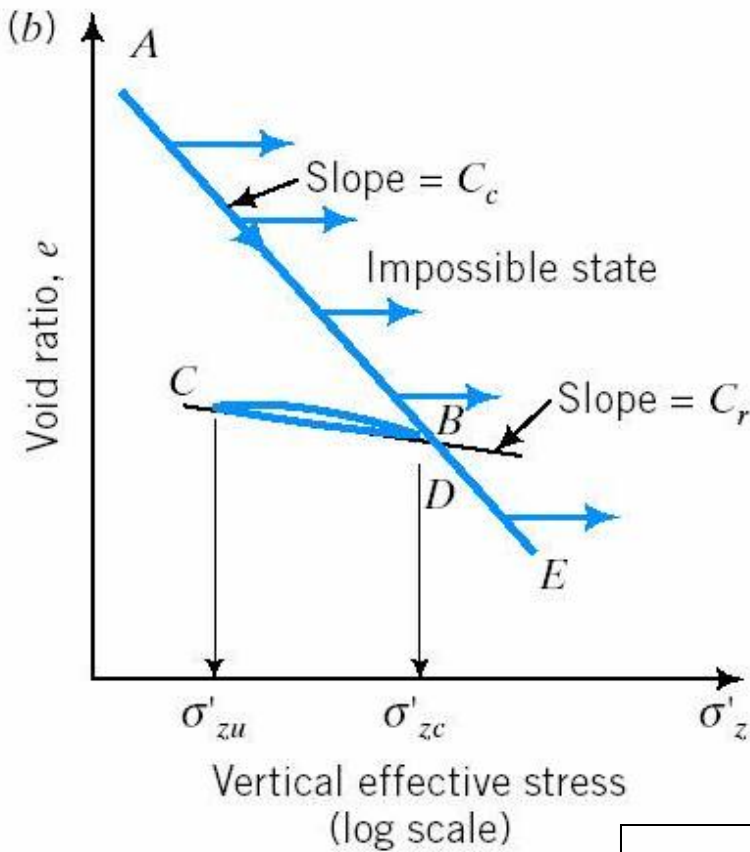
$$m_v = \Delta \varepsilon_z / \Delta \sigma'_z = \text{Modulus of volume compressibility}$$

# Drainage Path (p. 171 Budhu)

$$H_{dr} = \frac{H_{av}}{2} = \frac{H_o + H_f}{4} \quad (6.1)$$



# Primary Consolidation Parameters



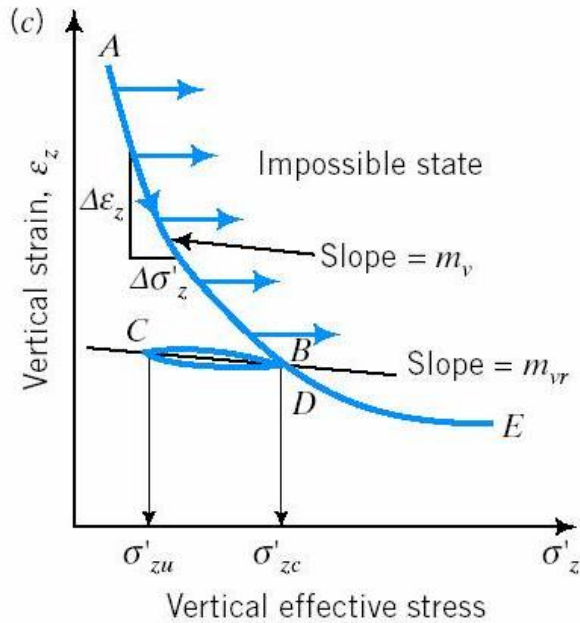
Compression Index  $\rightarrow$

$$C_c = -\frac{e_2 - e_1}{\log \frac{(\sigma'_z)_2}{(\sigma'_z)_1}} = \frac{|\Delta e|}{\log \frac{(\sigma'_z)_2}{(\sigma'_z)_1}} \quad (\text{no units}) \quad (6.7)$$

Recompression Index  $\rightarrow$

$$C_r = -\frac{e_2 - e_1}{\log \frac{(\sigma'_z)_2}{(\sigma'_z)_1}} = \frac{|\Delta e_r|}{\log \frac{(\sigma'_z)_2}{(\sigma'_z)_1}} \quad (\text{no units}) \quad (6.9)$$

# Primary Consolidation Parameters



$$E'_c = \frac{\Delta\sigma'_z}{\Delta\varepsilon_z} \quad (6.11)$$

Coefficient of Volume Compressibility

$$m_v = -\frac{(\varepsilon_z)_2 - (\varepsilon_z)_1}{(\sigma'_z)_2 - (\sigma'_z)_1} = \frac{|\Delta\varepsilon_z|}{(\sigma'_z)_2 - (\sigma'_z)_1} \quad \left(\frac{\text{m}^2}{\text{kN}}\right) \quad (6.8)$$

$$m_{vr} = -\frac{(\varepsilon_z)_2 - (\varepsilon_z)_1}{(\sigma'_z)_2 - (\sigma'_z)_1} = \frac{|\Delta\varepsilon_{zr}|}{\Delta\sigma'_z} \quad \left(\frac{\text{m}^2}{\text{kN}}\right) \quad (6.10)$$

# Overconsolidation Ratio (p. 175 Budhu)

$$\text{OCR} = \frac{\sigma'_{zc}}{\sigma'_{zo}} \quad (6.13)$$

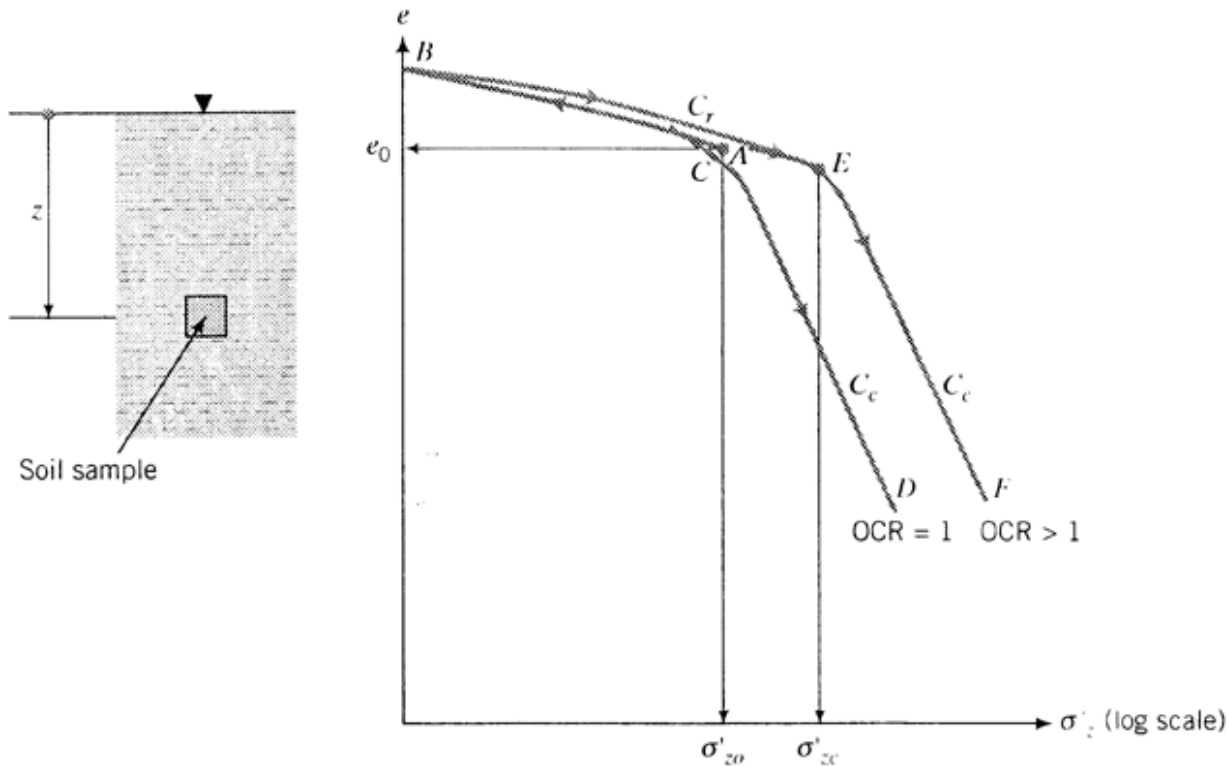


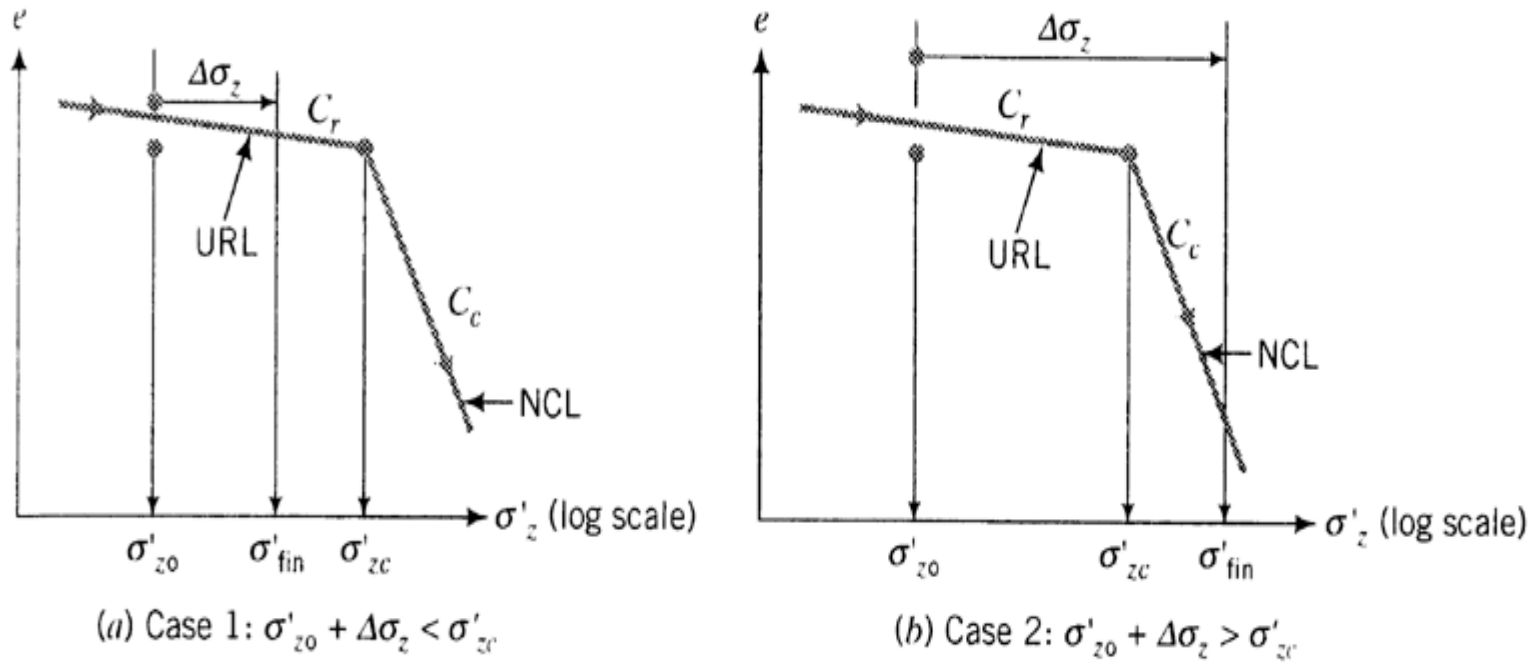
FIGURE 6.4 (a) Soil sample at a depth  $z$  below ground surface. (b) Expected one-dimensional response.

# Consolidation Status

$\sigma'_{z0}$  = Vertical Effective Stress in the Field (calculated)

$\sigma'_{zc}$  = Preconsolidation stress (laboratory determined)

- If  $\sigma'_{z0} \sim \sigma'_{zc}$ , vertical effective stress in the field has never been higher than its current magnitude. Soil in this condition is known as normally consolidated (NC). e.g., soil at the bottom of a natural, undredged lake.
- If  $\sigma'_{z0} < \sigma'_{zc}$  – this means vertical effective stress in the field once had been higher than its current magnitude. Soil in this condition is known as overconsolidated (OC).
  - Causes of overconsolidation
    - erosion
    - loading from past glaciers, structures
    - desiccation
    - GWT fluctuations
    - aging
    - chemical changes



**FIGURE 6.5** Two cases to consider for calculating settlement of overconsolidated fine-grained soils.

$$\sigma'_{\text{fin}} = \sigma'_{z0} + \Delta\sigma_z$$

#### 6.4.2 Primary Consolidation Settlement of NC Fine Grain (p. 177 Budhu, Wiley)

$$\rho_{pc} = H_o \frac{\Delta e}{1 + e_o} = \frac{H_o}{1 + e_o} C_c \log \frac{\sigma'_{\text{fin}}}{\sigma'_{z0}}; \quad \text{OCR} = 1 \quad (6.14)$$

#### 6.4.3 Primary Consolidation Settlement of OC Fine Grain (p. 177 Budhu, Wiley)

$$\rho_{pc} = \frac{H_o}{1 + e_o} C_r \log \frac{\sigma'_{\text{fin}}}{\sigma'_{z0}}; \quad \sigma'_{\text{fin}} < \sigma'_{zc} \quad (6.15)$$

$$\rho_{pc} = \frac{H_o}{1 + e_o} \left( C_r \log \frac{\sigma'_{zc}}{\sigma'_{z0}} + C_c \log \frac{\sigma'_{\text{fin}}}{\sigma'_{zc}} \right); \quad \sigma'_{\text{fin}} > \sigma'_{zc} \quad (6.16)$$

$$\rho_{pc} = \frac{H_o}{1 + e_o} \left[ C_r \log(\text{OCR}) + C_c \log \frac{\sigma'_{\text{fin}}}{\sigma'_{zc}} \right]; \quad \sigma'_{\text{fin}} > \sigma'_{zc} \quad (6.17)$$

# Example Problem

From a lab test of a sample taken at A, after geometric construction of field curve, it is given:

$$\sigma'_{zc} = 70 \text{ kPa}$$

$$C_c = 0.55; C_r = 0.55$$

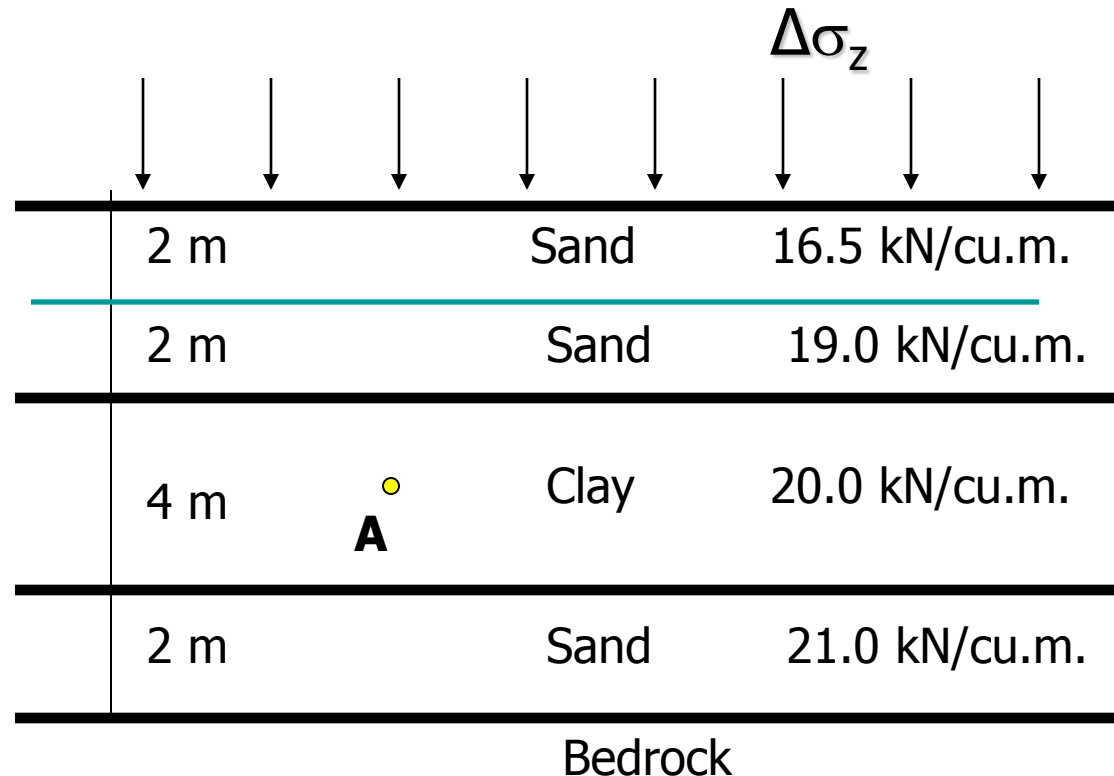
$$c_v = 1.0 \times 10^{-4} \text{ cm}^2/\text{sec}$$

$$e_0 = 1.08$$

It is also given that  $\Delta\sigma_z$  due to wide-area load =  $q = 16 \text{ kPa}$  is applied relatively quickly.

Compute for the clay layer:

- Total settlement
- Settlement vs time



1)  $\sigma'_c$  (centre of clay)  $\Rightarrow$

$$\sigma_{z0} =$$

$$u =$$

$$\sigma'_{z0} =$$

2) Clay N.C. or O.C.?

3) From constructed field compression  
curve  $\Rightarrow Cc =$

4)

7) Final consolidation settlement  $S_c$

$$\rho_{pc} = H_o \frac{\Delta e}{1 + e_o} = \frac{H_o}{1 + e_o} C_c \log \frac{\sigma'_{fin}}{\sigma'_{zo}}; \quad \text{OCR} = 1 \quad (6.14)$$

# Prediction of Settlements

## Single Soil Layer

Procedure:

- Use Equation 6.15 (for NC) and Equation 6.16 or 6.17 (for OC).
- Read Section 6.4.3 p. 178 Budhu text

## Thick Soil Layer

Procedure:

- Divide the deposit into a number of layers.
- Then use, Equation 6.15 (for NC) and Equation 6.16 or 6.17 (for OC) as per Section 6.4.3 Budhu text to get settlements for each layer.
- Note: The values of  $C_c$ ,  $e_0$ ,  $\sigma'_{z0}$ ,  $\sigma'_{zc}$ ,  $\Delta\sigma_z$ ,  $H_i$  correspond to those for a given layer.
- Sum up the settlements for each layer to get the total settlement.

# **One-dimensional Consolidation of Fine-grained Soils**

## ***Learning Objectives – Completed so far***

- Settlement of structures.
- General approach to computation of settlements.
- Common processes producing settlements (Primary/secondary compression, distortion)

## ***Learning Objectives – To be Completed***

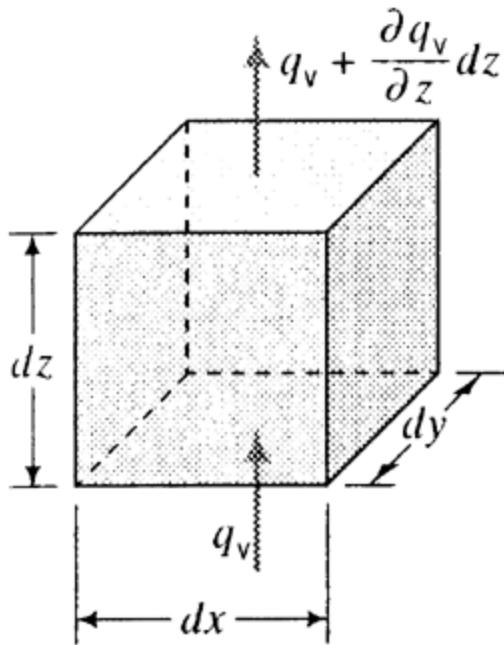
- Terzaghi one-dimensional consolidation theory
- Settlement analysis (Rates of consolidation and secondary settlement, Ultimate settlement)
- Methods for reducing settlements

# Terzaghi One-dimensional Theory of Consolidation

Basic Assumptions for the development of theory:

1. The soil is saturated, isotropic, and homogeneous;
2. Darcy's Law is valid;
3. Flow only occurs vertically (1-D consolidation process) and hydraulic conductivity ( $k_z$ ) is constant during the process;
4. The relationship between volume change and effective stress is independent of time but changes with level of stress;
5. Strains are relatively small;
6. The individual soil particles and water are incompressible;
7. Instantaneous increase in  $\Delta\sigma_z$  (total stress increase); afterwards no change in  $\Delta\sigma_z$  during the consolidation process;
8. Immediately after loading excess pore water pressure ( $\Delta u$ ) is constant with depth;
9. The coefficient of consolidation ( $c_v$ ) – we will define this later – is constant throughout the soil.

# Consolidation Theory



$$\text{Coefficient of Consolidation} = C_v = \frac{k_z}{m_v \gamma_w}$$

FIGURE 6.6 One-dimensional flow through a two-dimensional soil element.

$$\frac{\partial u}{\partial t} = C_v \frac{\partial^2 u}{\partial z^2} \quad (6.29)$$

Elev. head

6.5.2 Solution of Governing Equation by Fourier Series (p. 187 Budhu, Wiley)

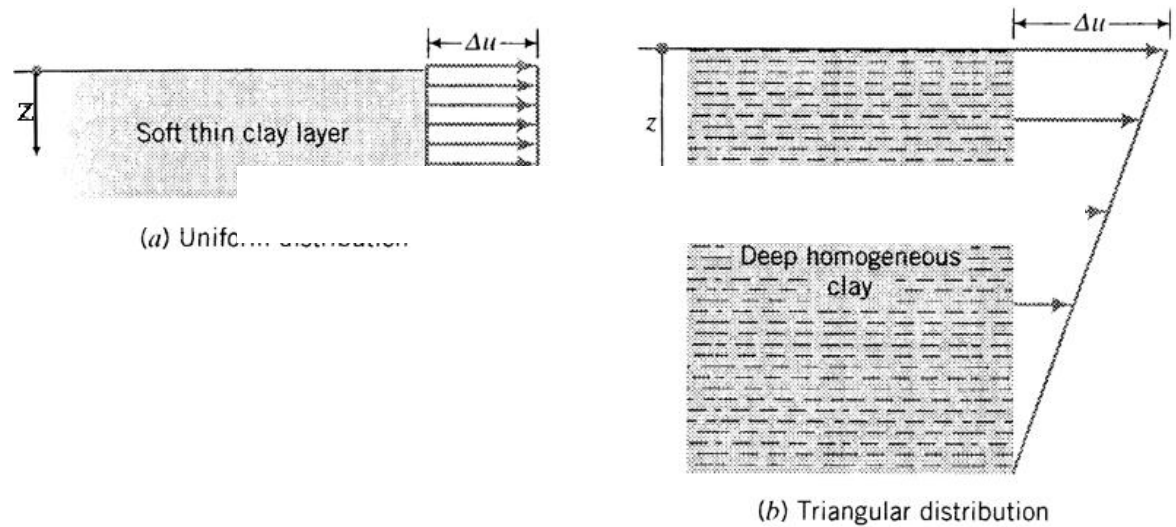


FIGURE 6.7 Two types of excess porewater pressure distribution with depth: (a) uniform distribution with depth in a thin layer and (b) triangular distribution with depth in a thick layer.

Now, consider uniform distribution of initial excess pore water pressure with depth (i.e., Figure 6.7(a) of Budhu text).

Layer of thickness  $2 \cdot H_{dr}$  with two free draining boundaries at the top and base of layer.

Boundary Conditions:

@  $t = 0$   $\Delta u = \Delta u_0 = \Delta \sigma_z$  for  $0 < z < 2d$ ;

At top boundary,  $z = 0$   $\Delta u = 0$

At bottom boundary,  $z = 2H_{dr}$ ,  $\Delta u = 0$ ,  $H_{dr}$  = drainage path length

## 6.5.2 Solution of Governing Equation by Fourier Series (p. 187 Budhu, Wiley)

$$\Delta u(z, t) = \sum_{m=0}^{\infty} \frac{2\Delta u_o}{M} \sin\left(\frac{Mz}{H_{dr}}\right) \exp(-M^2 T_v) \quad (6.30)$$

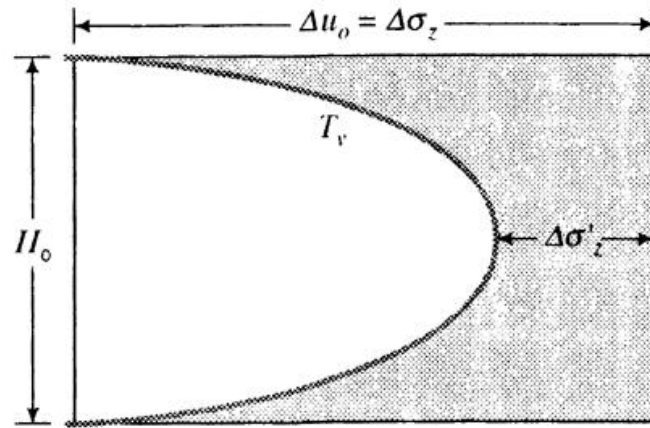
$$M = (\pi/2)(2m+1)$$

and  $m$  is a positive integer from 0 to infinity.

$$T_v = \frac{C_v t}{H_{dr}^2} \quad (6.31)$$

$T_v =$  Time Factor  $\rightarrow$  non-dimensional

## 6.5.2 Solution of Governing Equation by Fourier Series (p. 187 Budhu, Wiley)



**FIGURE 6.8** An isochrone illustrating the theoretical excess porewater pressure distribution with depth.

Degree of consolidation at a given depth and time

$$U_z = 1 - \frac{\Delta u_z}{\Delta u_o} = 1 - \sum_{m=0}^{\infty} \frac{2}{M} \sin\left(\frac{Mz}{H_{dr}}\right) \exp(-M^2 T_v) \quad (6.32)$$

Average degree of consolidation over the full thickness

$$U = 1 - \sum_{m=0}^{\infty} \frac{2}{M^2} \exp(-M^2 T_v) \quad (6.33)$$

# Simplified set of equations for average degree of consolidation

$$T_v = \frac{\pi}{4} \left( \frac{U}{100} \right)^2 \quad \text{for } U < 60\% \quad (6.34)$$

$$T_v = 1.781 - 0.933 \log(100 - U) \quad \text{for } U \geq 60\% \quad (6.35)$$

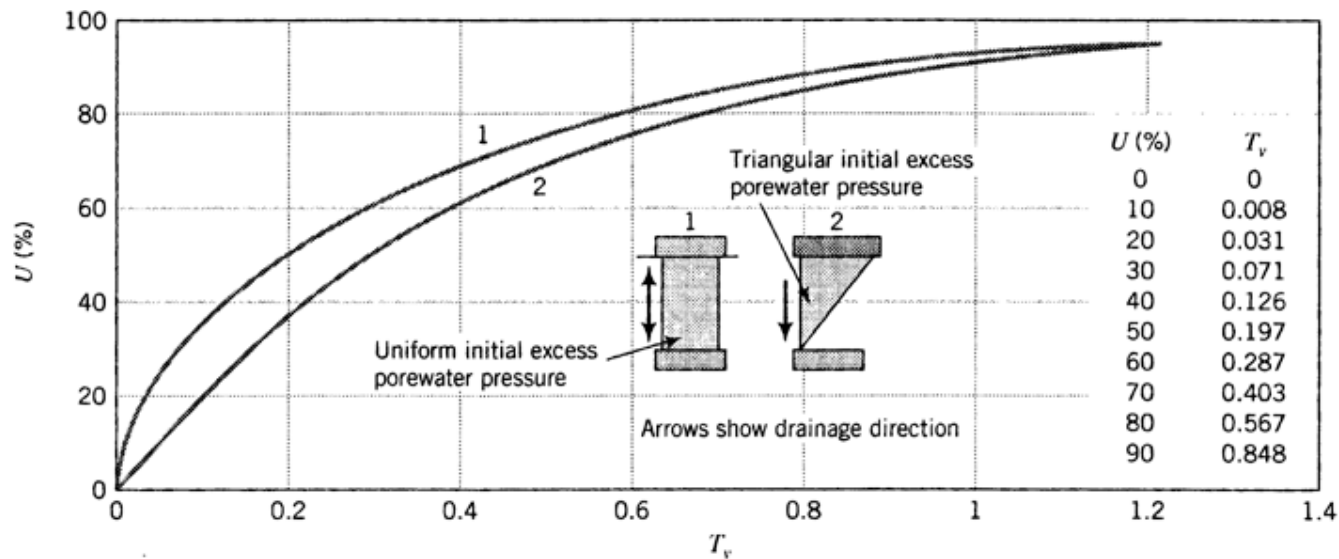


FIGURE 6.9 Relationship between time factor and average degree of consolidation for a uniform distribution and a triangular distribution of initial excess porewater pressure.

# Example Problem

From a lab test of a sample taken at A, after geometric construction of field curve, it is given:

$$\sigma'_{zc} = 70 \text{ kPa}$$

$$C_c = 0.55; C_r = 0.55$$

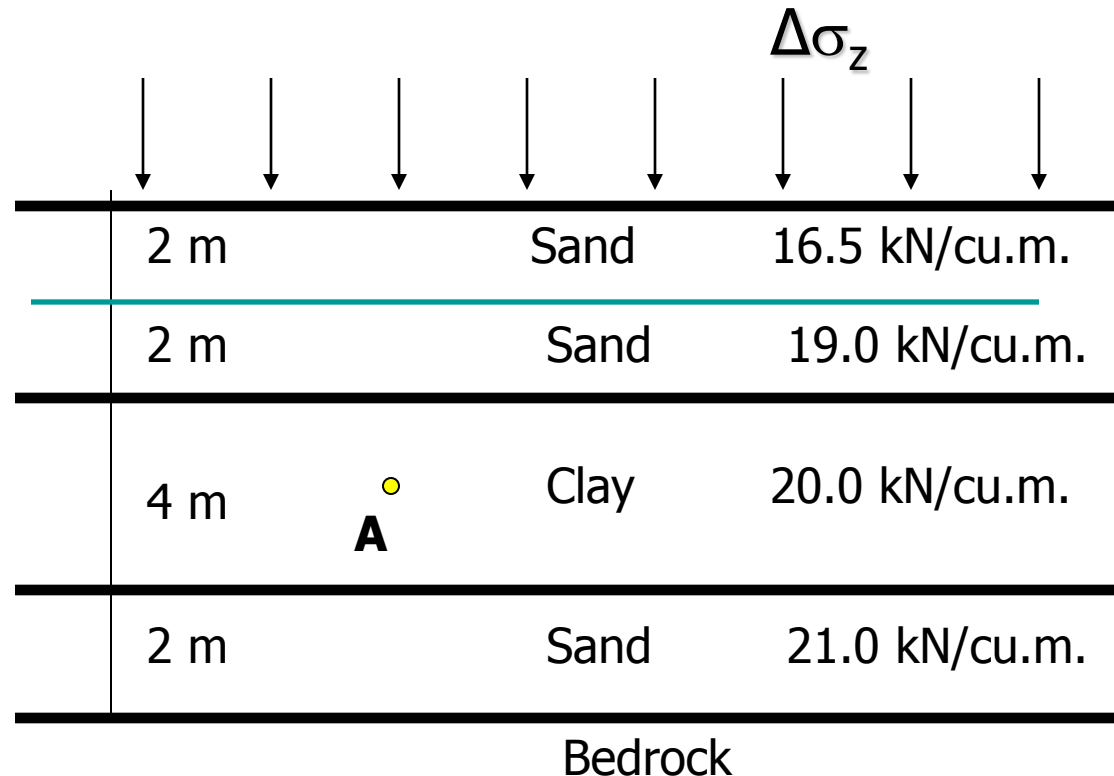
$$c_v = 1.0 \times 10^{-4} \text{ cm}^2/\text{sec}$$

$$e_0 = 1.08$$

It is also given that  $\Delta\sigma_z$  due to wide-area load =  $q = 16 \text{ kPa}$  is applied relatively quickly.

Compute for the clay layer:

- Total settlement
- Settlement vs time



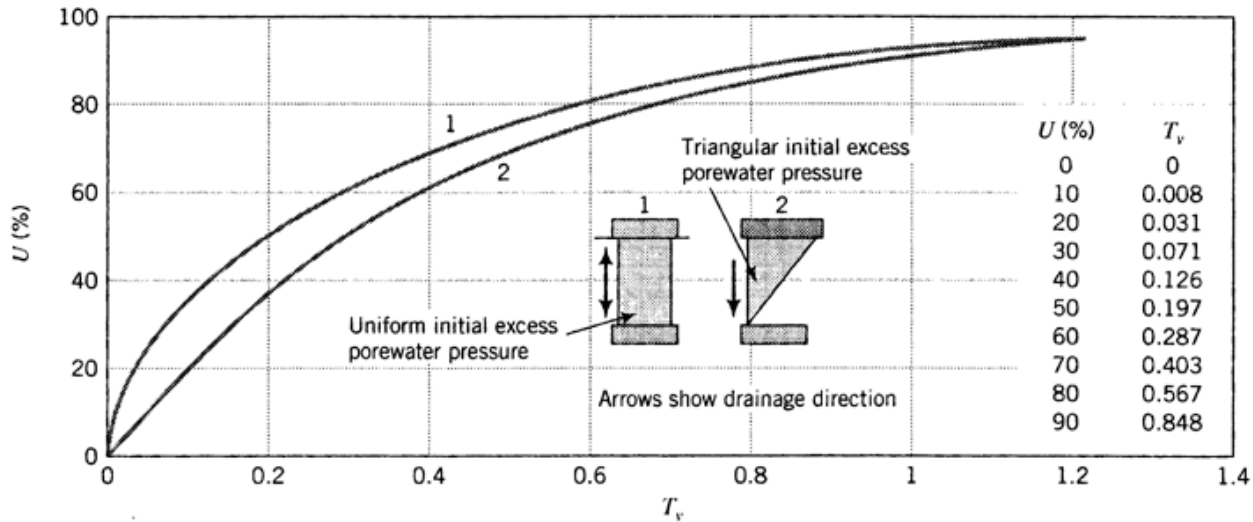


FIGURE 6.9 Relationship between time factor and average degree of consolidation for a uniform distribution and a triangular distribution of initial excess porewater pressure.

### 8) Rate of settlement

i.e.,  $\rho$  vs  $t$

$$S = U \rho_{pc}$$

$$U = f(T_v) \text{ see figure above}$$

$$T_v = (c_v \cdot t) / (H_{dr})^2$$

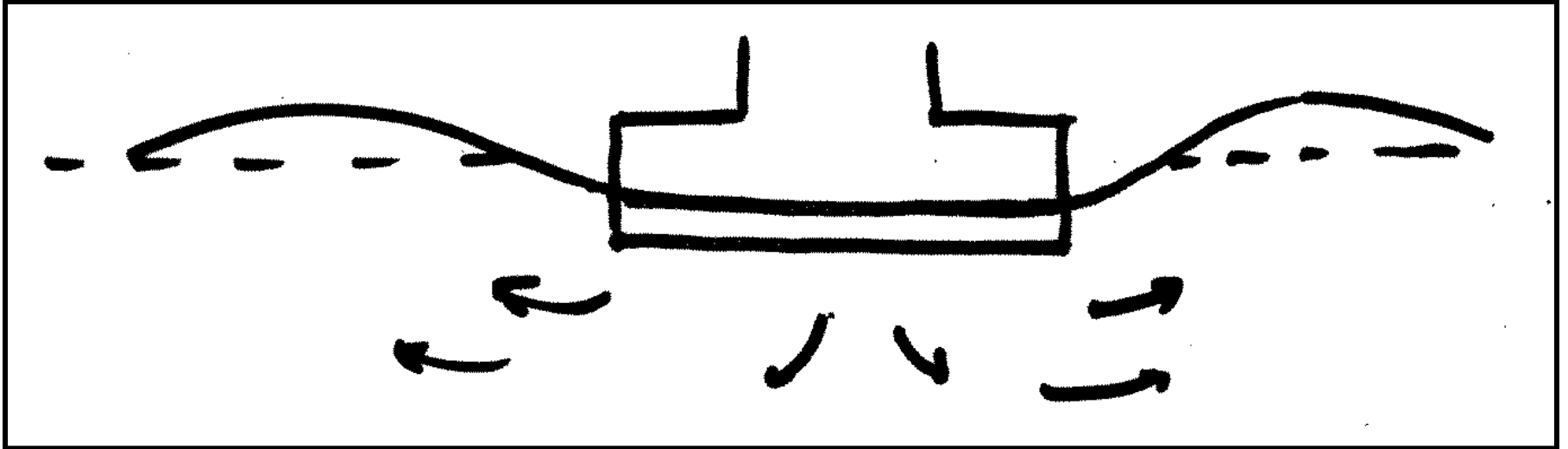
$$c_v = 1.0 \times 10^{-4} \text{ cm}^2/\text{s} \quad \sigma'_{zo} \rightarrow \sigma'_{fin}$$

$$H_{dr} = \quad \text{m}$$

$$T_v = \quad \text{years} = \quad \text{sec}$$

	$t_{\text{years}}$	1	2	4	8	16
	$T_v$	0.08	0.16	0.32	0.64	1.28
	$U$	0.32	0.45	0.63	0.83	0.97
$S_{ct}$	$U \rho_{pc}$					

# Settlements Due to Distortion



This is a deviation from the 1-D case we have examined so far. Settlements due to distortion will be addressed elsewhere.

# Secondary Compression Settlement

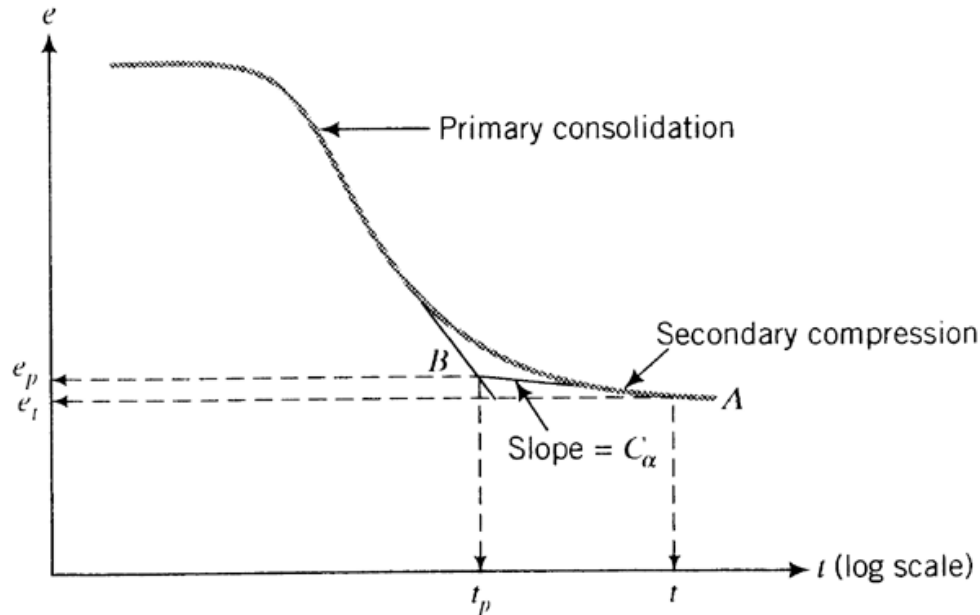


FIGURE 6.11 Secondary compression.

$$C_\alpha = -\frac{(e_i - e_p)}{\log(t / t_p)}; t > t_p \quad \text{Equation 6.41}$$

$$\rho_{sc} = \frac{H_0}{(1 + e_p)} C_\alpha \log(t / t_p) \quad \text{Equation 6.42}$$

# Consolidation Test

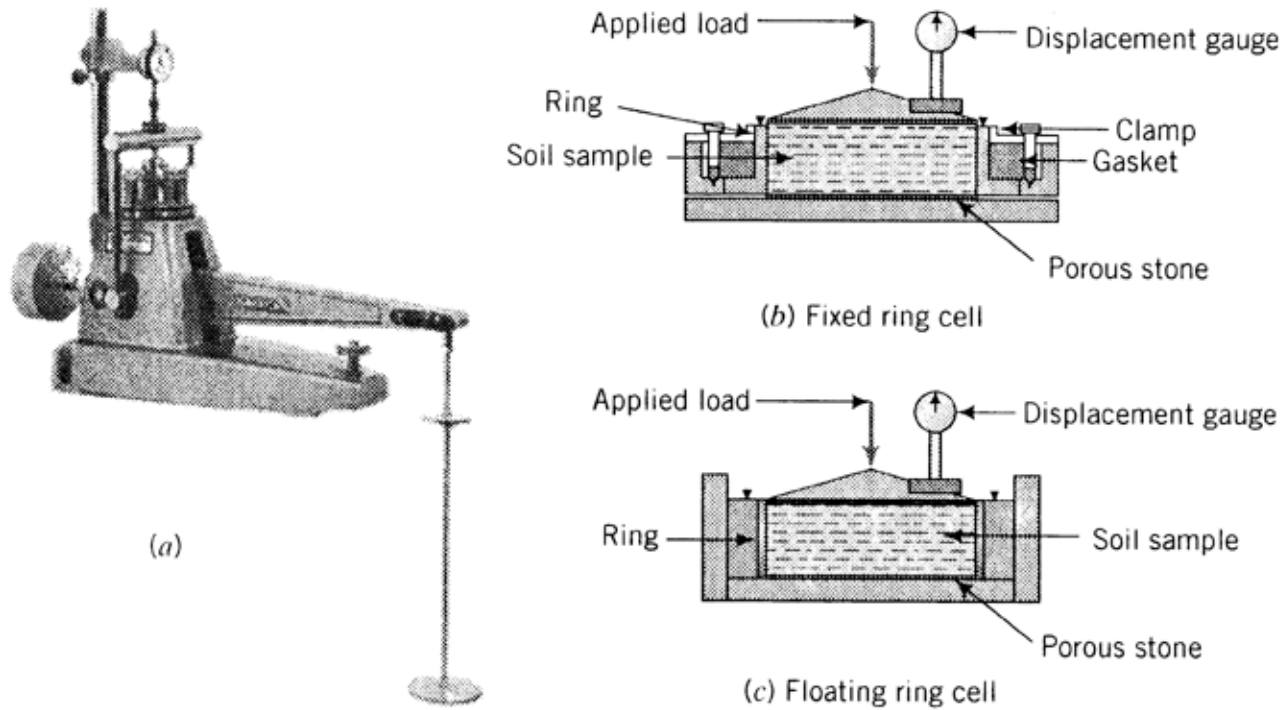
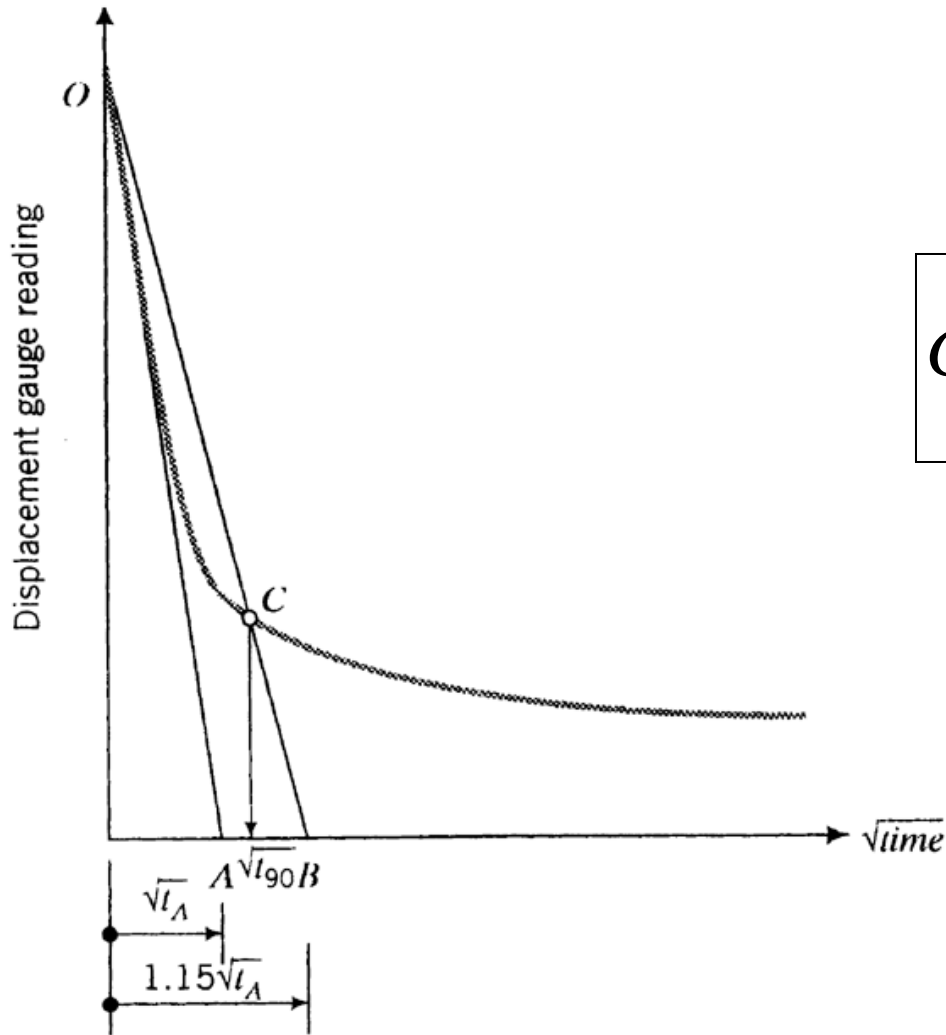


FIGURE 6.12 (a) A typical consolidation apparatus (photo courtesy of Geotest), (b) a fixed ring cell, and (c) a floating ring cell

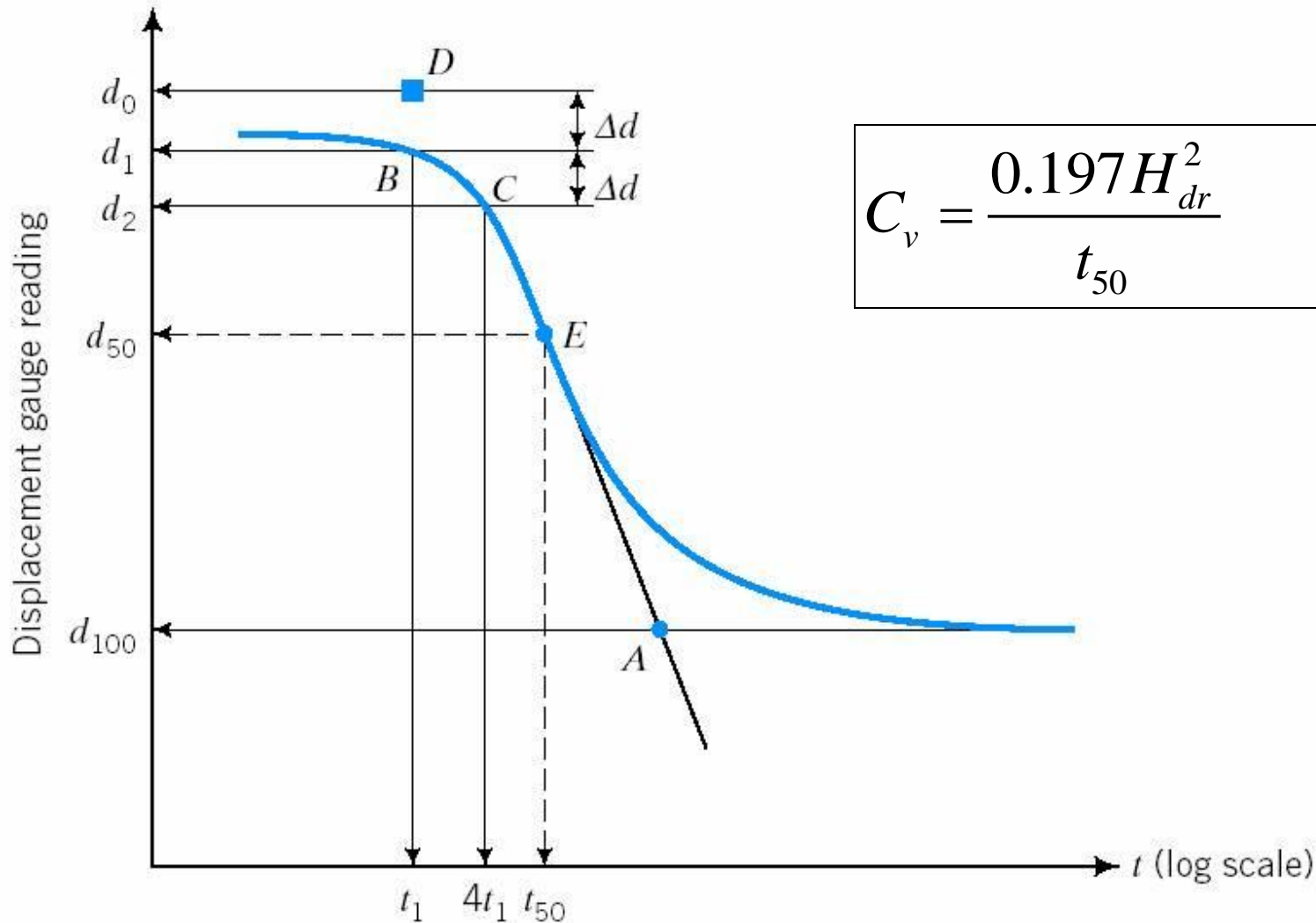
# Determination of $C_v$ – Root Time Mtd.



$$C_v = \frac{0.848H_{dr}^2}{t_{90}} \quad (6.43)$$

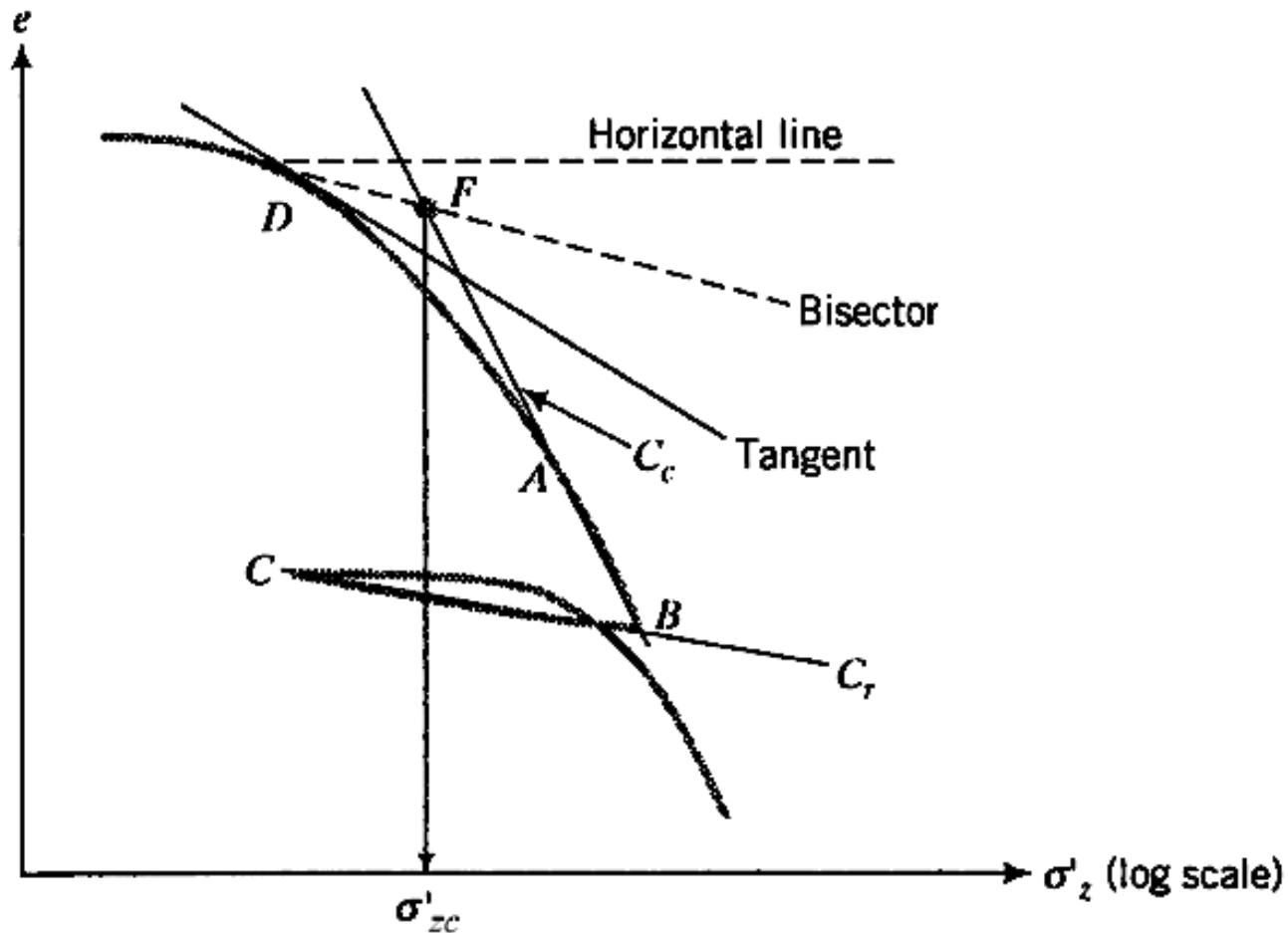
FIGURE 6.14 Root time method to determine  $C_v$ .

# Determination of $C_v$ – Log Time Mtd.



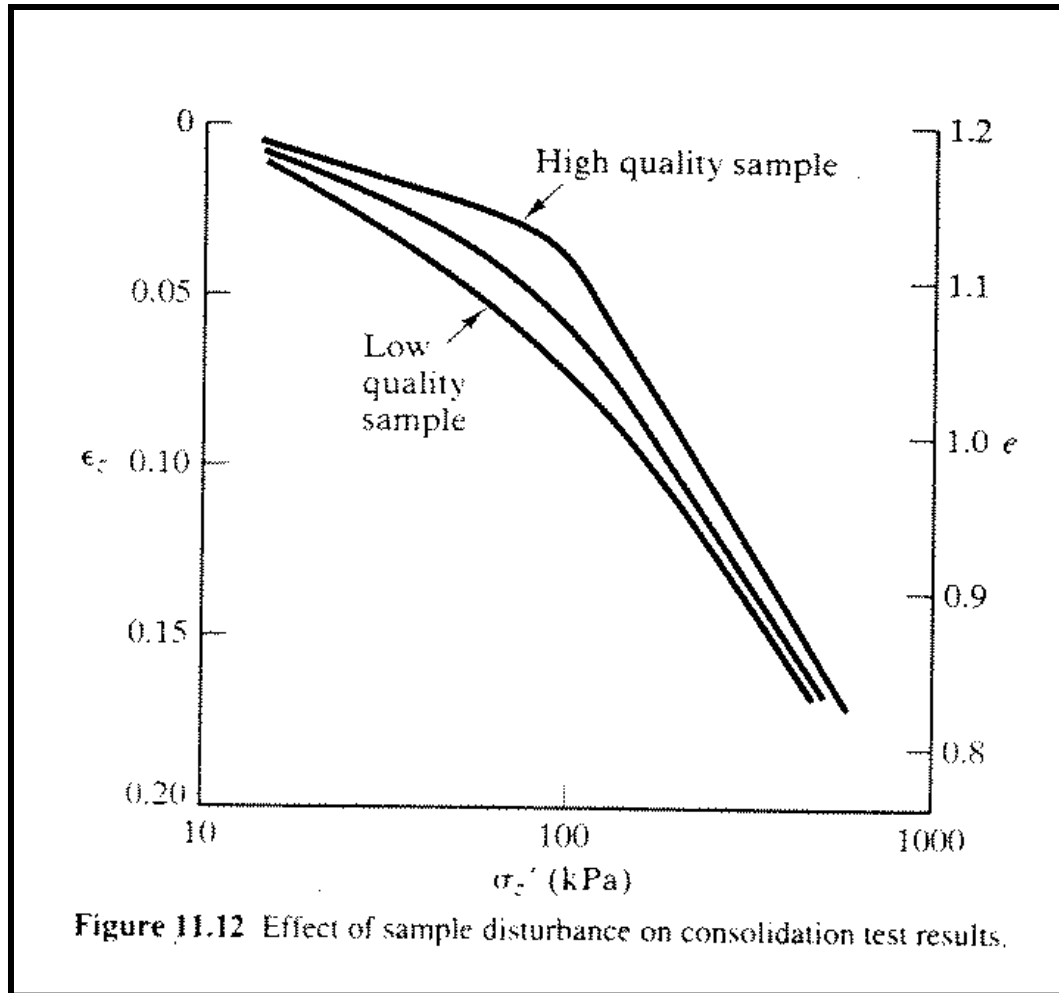
$$C_v = \frac{0.197 H_{dr}^2}{t_{50}} \quad (6.44)$$

# Determination of $\sigma'_{zc}$



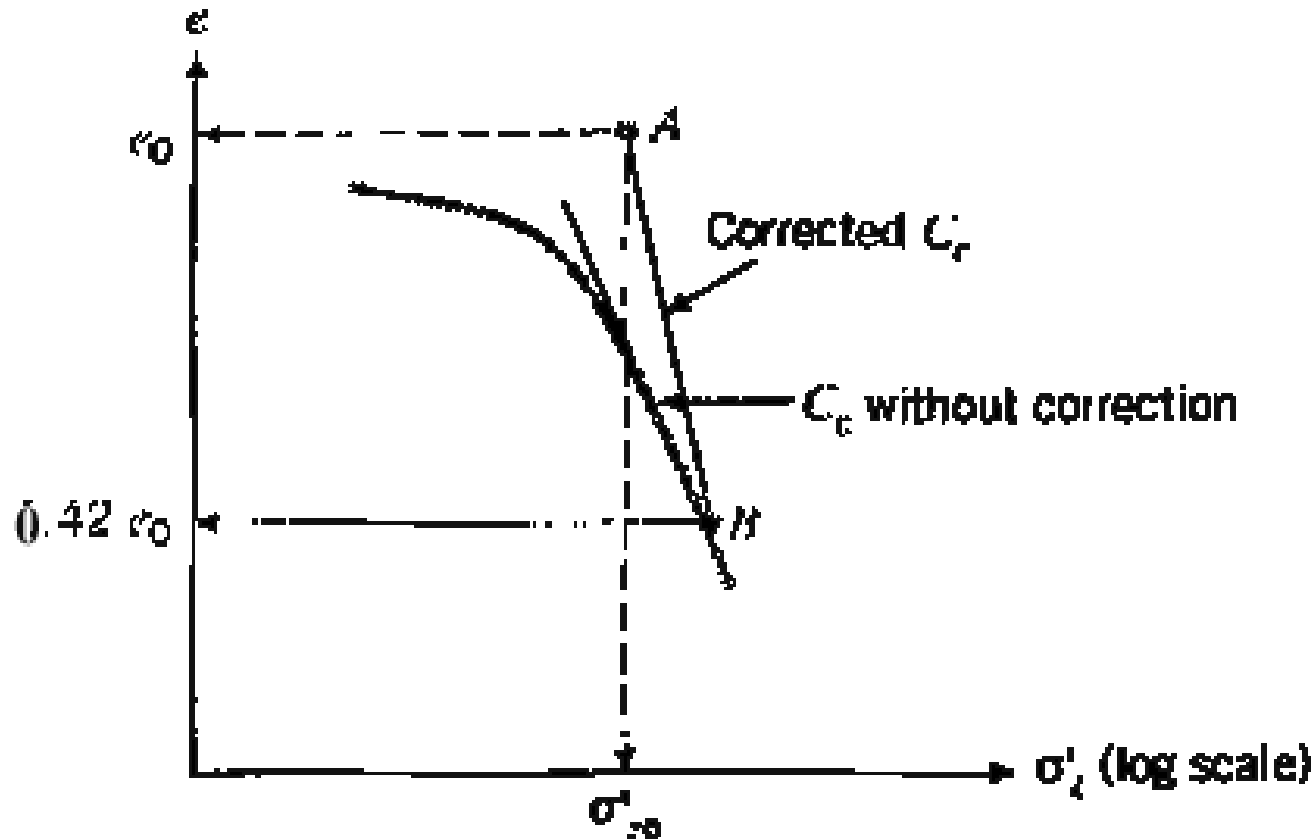
**FIGURE 6.16** Determination of the preconsolidation stress using Casagrande's method.

# Effect of sample disturbance



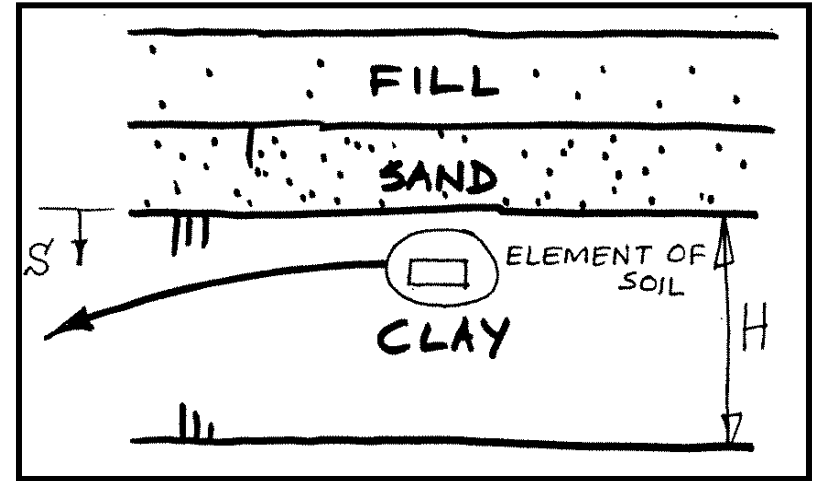
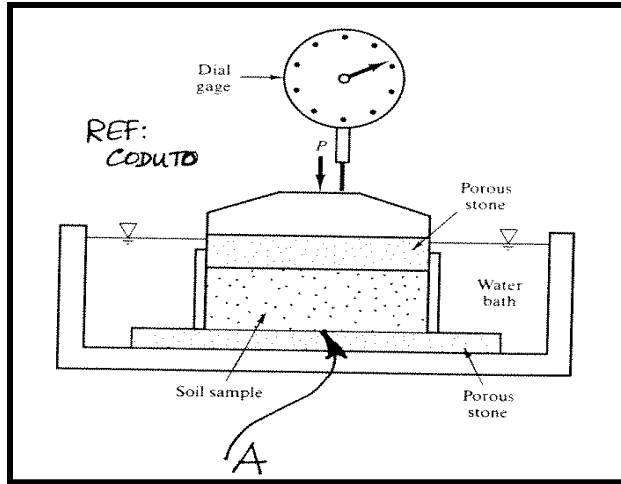
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# Correction of $e \log \sigma'_z$ curve



**FIGURE 6.18** Schmertmann's method to correct  $C_c$  for soil disturbances.

# Relationship between Laboratory And Field Consolidation



$$\frac{t_{\text{field}}}{t_{\text{lab}}} = \frac{\left(H_{dr}^2\right)_{\text{field}}}{\left(H_{dr}^2\right)_{\text{lab}}} \quad (6.46)$$

# Typical Values of Consolidation Settlement Parameters & Empirical Relationships

(1) See Section 6.9 Budhu Text - Book 1

Table 6.1. Empirical relationships between compressibility indices and index or physical properties.

Empirical equation	Author
$C_c = 0.007 (LL - 7)$	Skempton (1944)
$C_c = 0.009 (LL - 10)$	Terzaghi & Peck (1967)
$C_c = 0.37 (e_0 + 0.003 LL + 0.0004 w_n - 0.34)$	Azzouz et al. (1976)
$C_c = 0.48827 (\gamma_w / \gamma_d)^{0.19167}$	Rendon - Herrero (1980)
$C_c = 0.009 w_n + 0.005 LL$	Koppula (1986)
$C_c = -0.156 + 0.411 e_0 + 0.00058 LL$	Al-Khafaji & Andersland (1992)
$C_r = 0.14 (e_0 + 0.007), C_r = 0.003 (w_n + 7)$	Azzouz et al. (1976)
$C_r = 0.00566 w_n - 0.037, C_r = 0.00463 LL - 0.013$	Balasubramaniam & Brenner (1981)
$C_r = 0.00463 LL G_s$	Nagaraj & Srinivasa Murthy (1985)
$C_\alpha / C_c = 0.032, 0.025 < C_\alpha < 0.1$	Mesri & Godlewski (1977)
$C_\alpha / C_c = 0.06 \text{ to } 0.07, \text{ Peats, organic soils}$	Mesri (1986)
$C_\alpha / C_c = 0.015 \text{ to } 0.030, \text{ Sandy clays}$	Mesri et al. (1990)

# Methods to Reduce Post-construction Consolidation Settlements

- Removal of unsuitable soils and replacement
- Preloading
- Use of light-weight materials
- Use of grouting methods
- In situ replacement (deep soil mixing)

# Preloading to reduce post-construction consolidation settlements

Precompression of soil with a temporary surcharge fill.

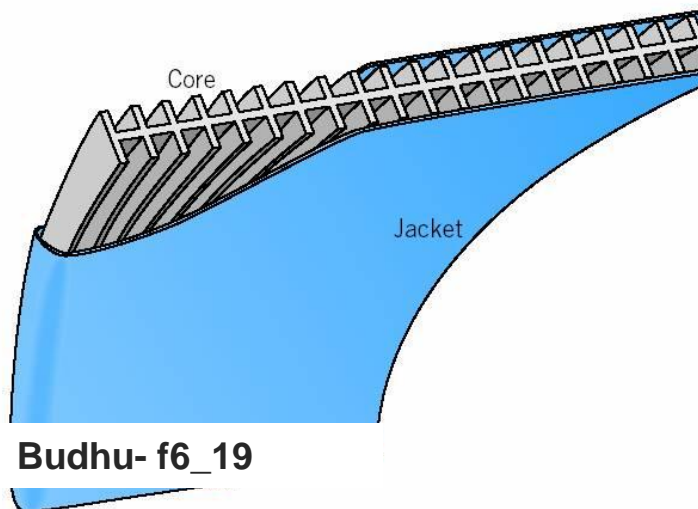
For example, preload the site to make:

$(\Delta\sigma'_z)_{\text{Preload}} = (\Delta\sigma'_z)_{\text{fill}}$   
in the clay zone

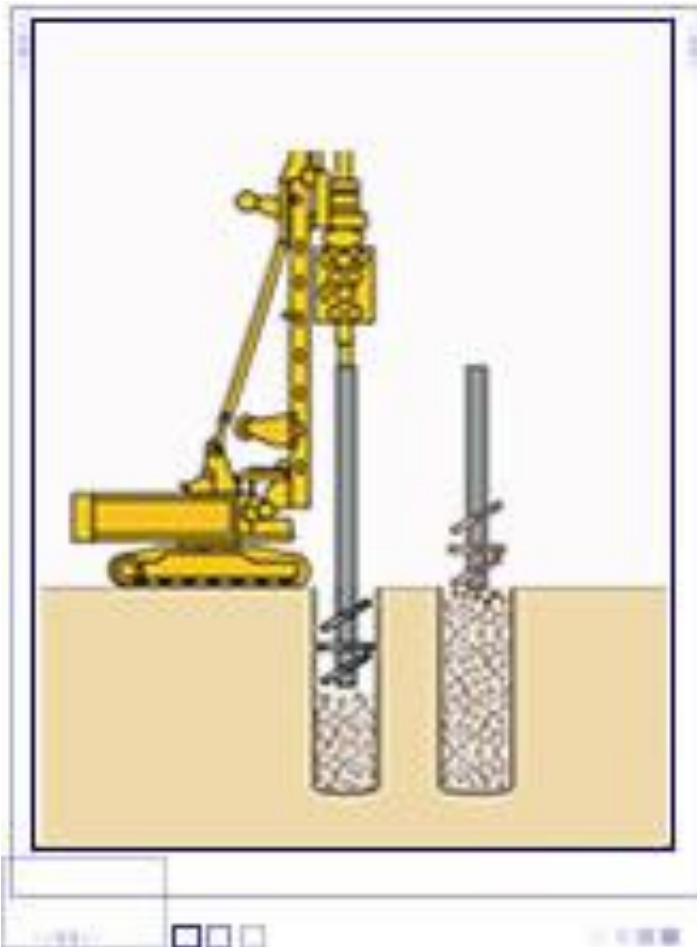


But this would be OK only if preload can be left for a very long time → Examine the effect preloading process from  $e$  vs  $\log \sigma'$  point of view

# Use of Wick Drains to expedite dissipation of pore water pressures



## Deep soil mixing

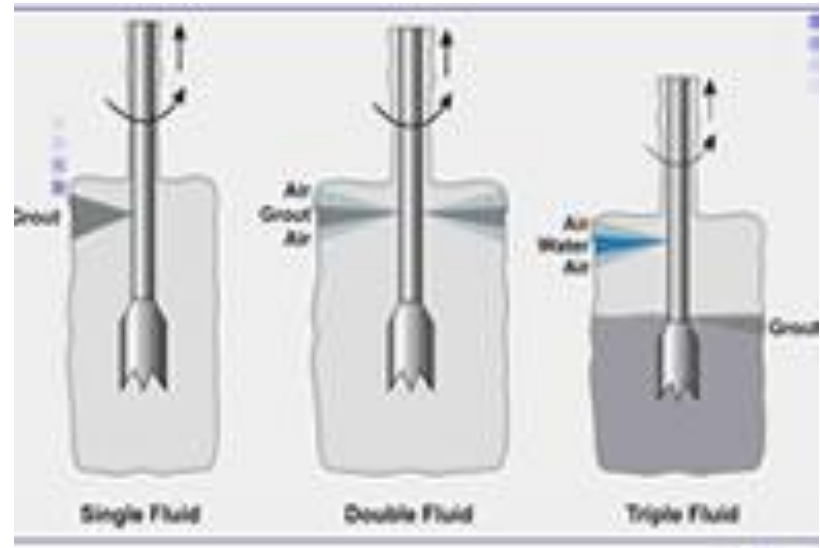
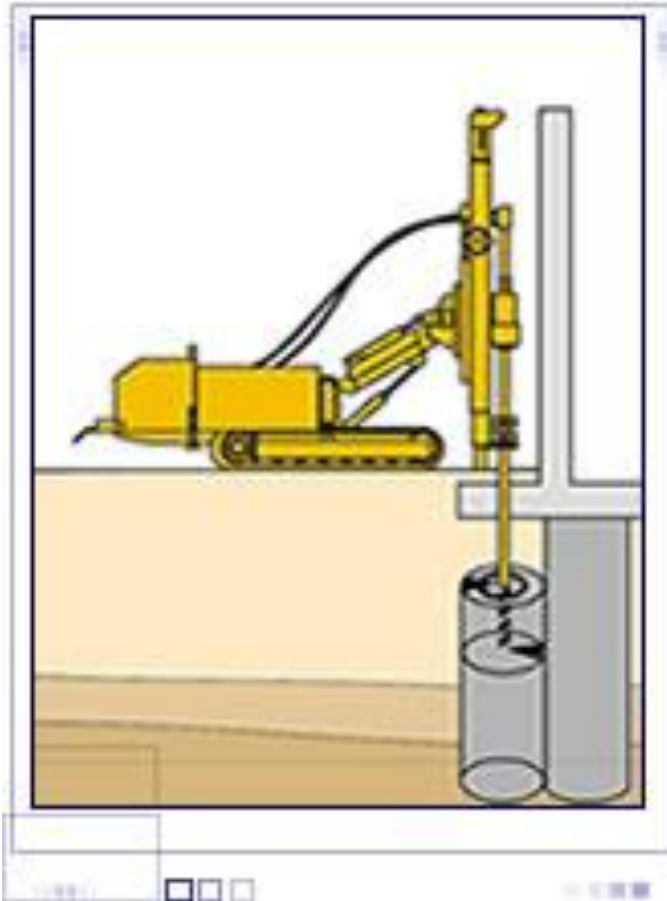


[www.haywardbaker.com](http://www.haywardbaker.com)



[www.geo-solutions.com/images/image004](http://www.geo-solutions.com/images/image004)

# Jet Grouting



# Previous Example Problem with Preloading

From a lab test of a sample taken at A, after geometric construction of field curve, it is given:

$$\sigma'_{zc} = 70 \text{ kPa}$$

$$C_c = 0.55; C_r = 0.55$$

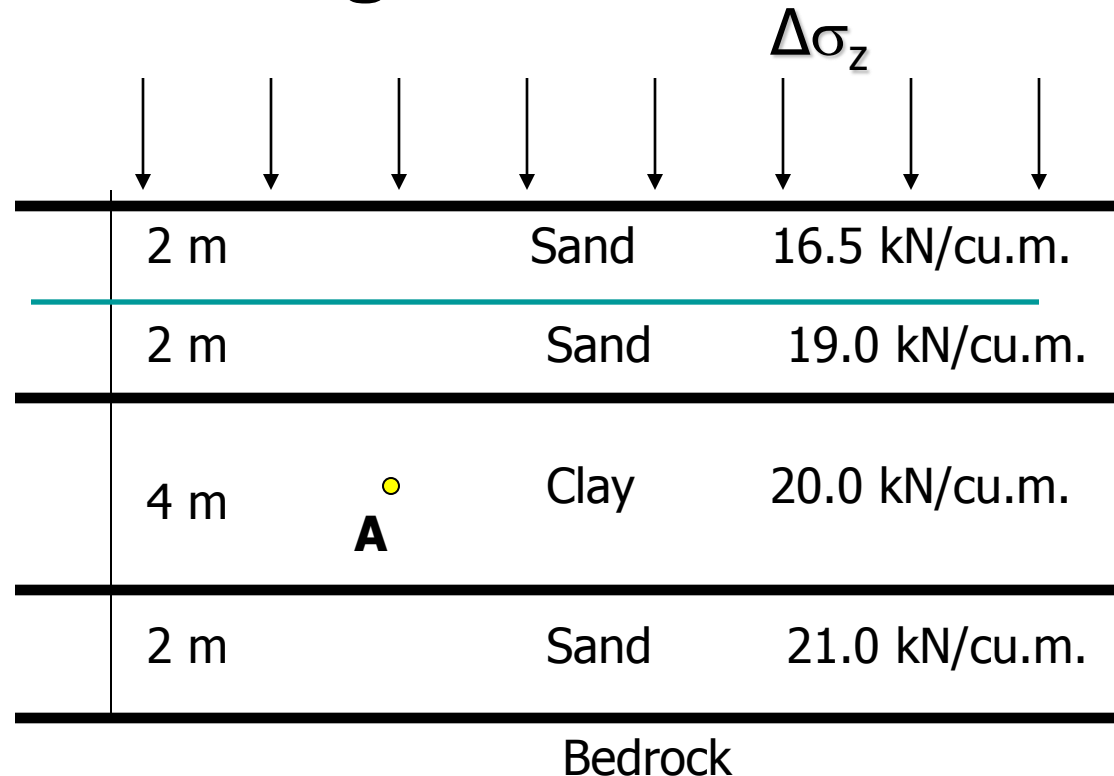
$$c_v = 1.0 \times 10^{-4} \text{ cm}^2/\text{sec}$$

$$e_0 = 1.08$$

It is also given that  $\Delta\sigma_z$  due to wide-area load =  $q = 16 \text{ kPa}$  is applied relatively quickly.

Compute for the clay layer:

- Total settlement
- Settlement vs time



# Example Problem

- Consider the last example. Let us say that you would like to reduce post-construction settlements by preloading. Then, ideally, @ centre of clay layer you want to achieve  
⇒

$$(\Delta\sigma'_z)_{\text{@ end of preloading}} = (\Delta\sigma_z)_{\text{from future load}}$$

$$(\Delta\sigma'_z)_{\text{@ end of preloading}} = 16 \text{ kPa}$$

- However, you would like achieve the overconsolidation effect relatively quickly. Say, you want to achieve this in 6 months → by placing a larger load.

# Example continued: Preloading

- Objective: reduce post-construction settlements by preloading.
- Contractor's schedule: Preloading time  $\leq 6$  months
- Let us:
  - (i) Find reduction in settlement if we preload the site under its final load for 6 months
  - (ii) Design preload to minimize post-construction settlement

# Example continued: Preloading

(1) Find reduction in settlement if we preload the site using its final load

$$q = 16 \text{ kPa}$$

$$\Delta\sigma_z = 16 \text{ kPa}$$

After 0.5 year

$$T_v = 0.04$$

$$U_{t=0.5\text{yr}} = 0.22$$

$$S_{t=0.5\text{yr}} =$$

Use chart or equation

$$T_v < 0.217 (U \leq 52.6\%)$$

$$U = \sqrt{\frac{4T_v}{\pi}} * 100\%$$

# Example continued: Preloading

(2) Now let us compute  $U$  after 0.5 years  $\rightarrow$

$$T_v = 0.08 \text{ t (calculated earlier, see last example)}$$

$\Downarrow$

$$T_v < 0.217 (U \leq 52.6\%)$$

$$U = \sqrt{\frac{4T_v}{\pi}} * 100\%$$

$\Downarrow$

This means:

$$U = 0.225$$

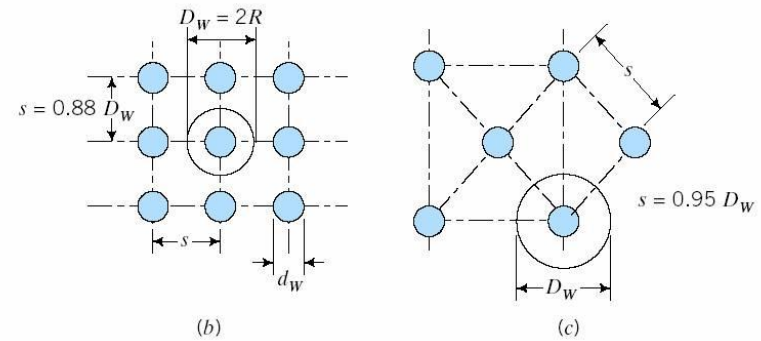
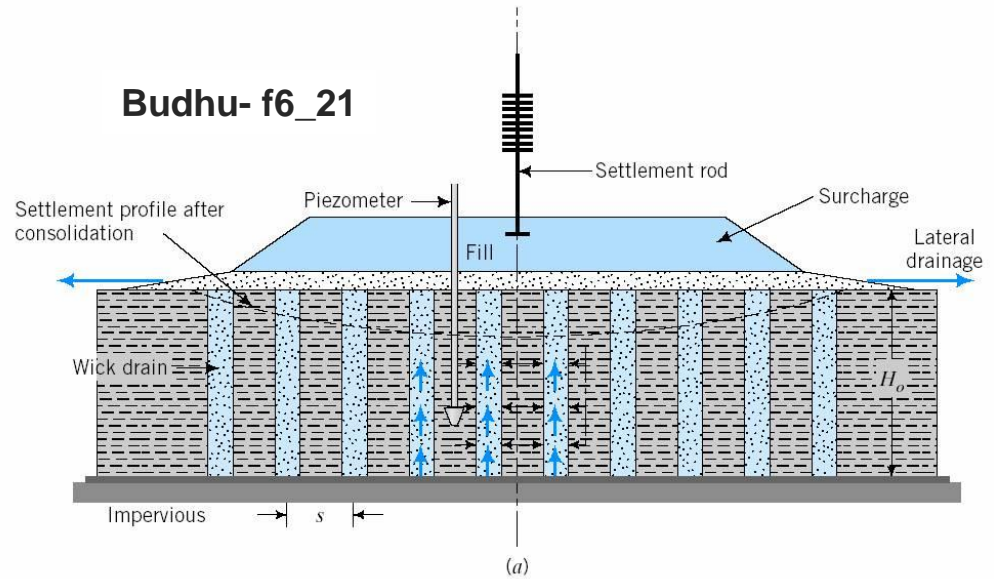
$$\frac{\sigma'_{av} - \sigma'_0}{(\Delta\sigma)_{preload}} = \frac{16}{(\Delta\sigma)_{prel.}} =$$

$$\Rightarrow (\Delta\sigma)_{prel.} = \quad \text{kPa}$$

Assume density of preload = 17 kN/m<sup>3</sup>

$\Rightarrow$  Thickness of preload =

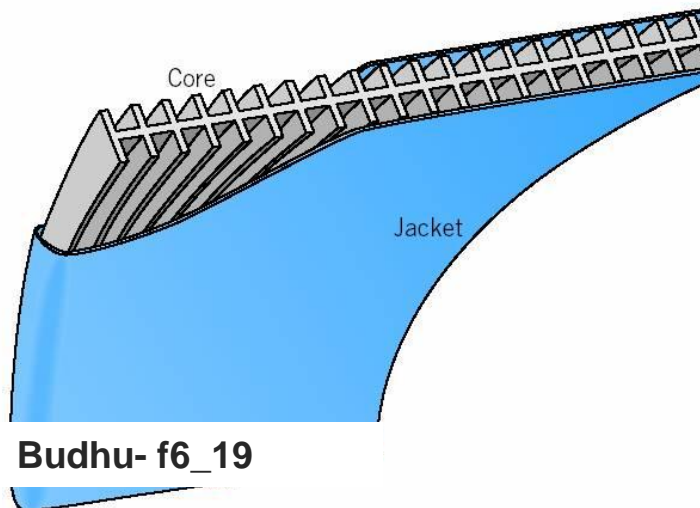
# Use of Drains to Expedite Dissipation of Excess Pore Water Pressures (i.e., Expedite Consolidation Settlements)

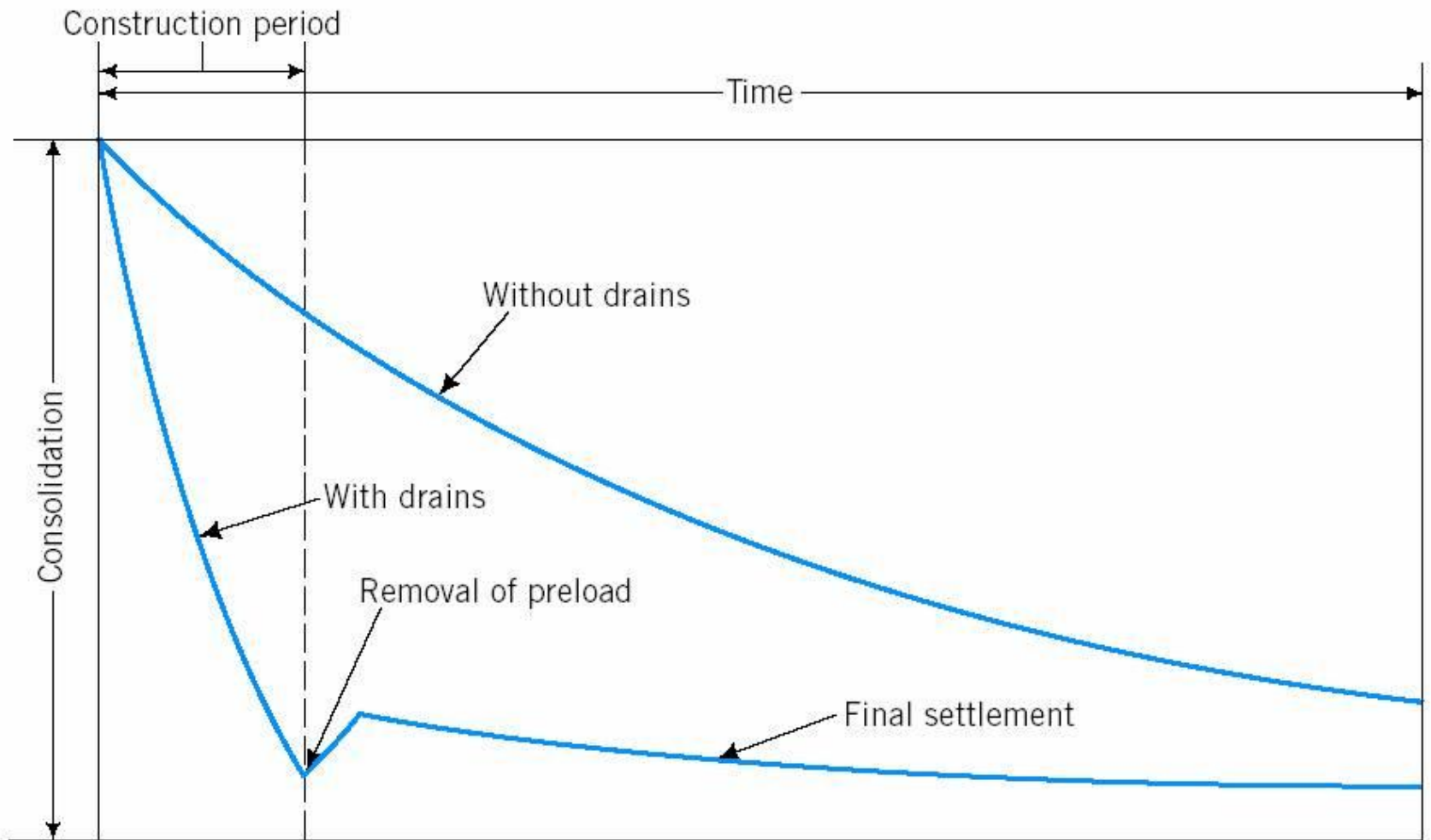


Providing artificial paths for pore water to escape

- Vertical sand drains
- Prefabricated vertical drains (wick drain)

# Use of prefabricated vertical drains to expedite dissipation of pore water pressures



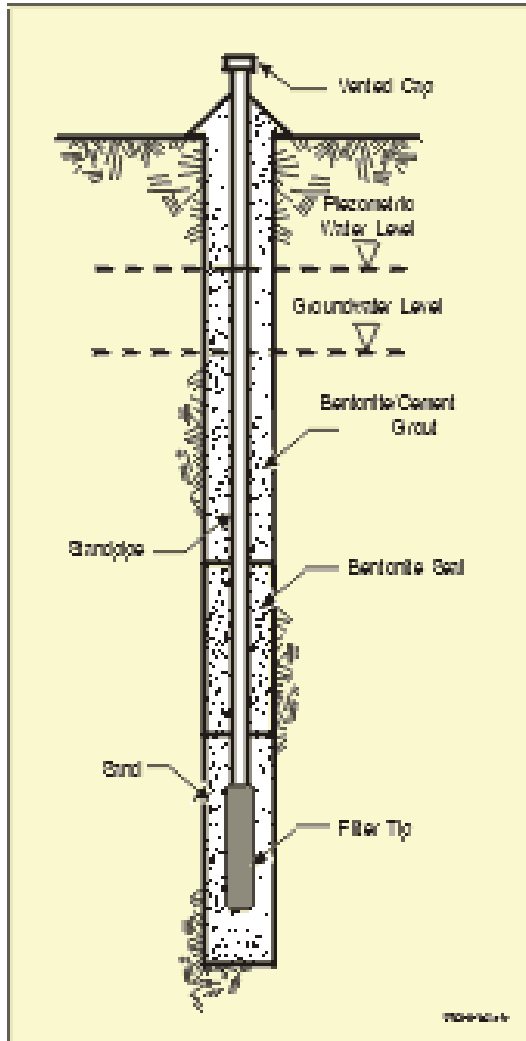


# Preloading – Engineering Considerations

- Uncertainties in preload design
  - Laboratory driven parameters vs field behaviour
  - Soil variability
  - Existence of permeable layers layers/ fissures
  - Anisotropy of coefficient of consolidation  $C_h > C_v$  (usually)
- Instrumentation
- Preload test
- Ground failure (limitation to preload)
- Preloading close to other structures

# Piezometers

## Stand pipe



## Push in Piezometers



[www.rstinstruments.com](http://www.rstinstruments.com)

# One-dimensional Consolidation of Fine-grained Soils

## *Learning Objectives Completed*

- Settlement of structures.
- General approach to computation of settlements.
- Common processes producing settlements (Primary/secondary compression, distortion)
- Terzaghi one-dimensional consolidation theory
- Settlement analysis (Rates of consolidation and secondary settlement, Ultimate settlement)
- Methods for reducing settlements