EWCE 341

Principles of Soil Mechanics

Consolidation

Ex. 2: Find out the **vertical effective stress** in soil element at point A, when a 5-m deep fill is placed shown in the following figure; after the consolidation is completed in the field.

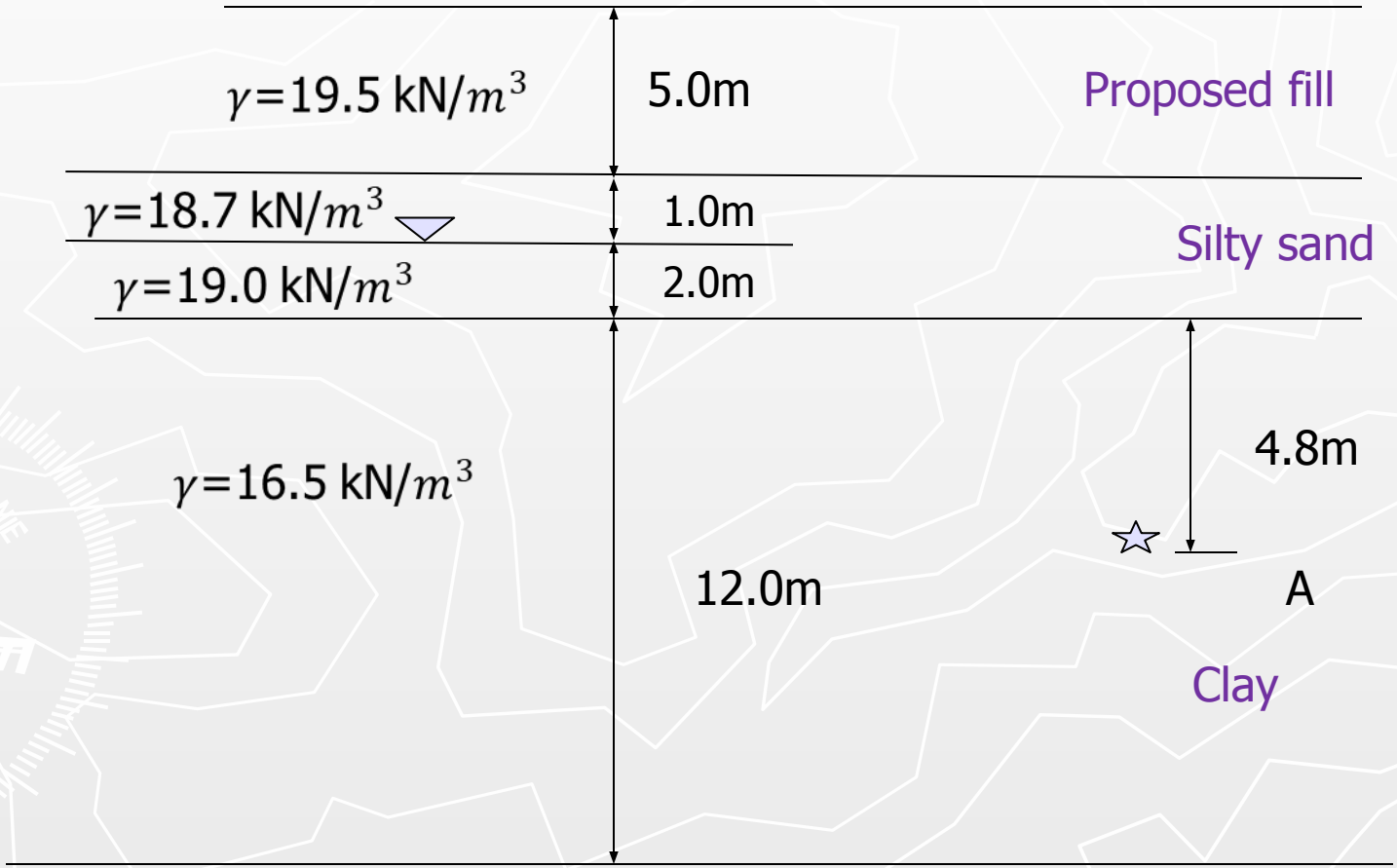


Figure: Soil Profile

Solution:

- Soil element is initially subjected to the following stresses:

$\sigma'_{z0} = \sigma_{z0} - u$

$\sigma_{z0} = \sum \gamma H$

$= 18.7 \times 1.0 + 19.0 \times 2.0 + 16.5 \times 4.8$

$= 136$ kPa

$u = \gamma_w z_w$

$= 9.8 \times (2.0 + 4.8)$

$=$ **67.0 kPa**

$\sigma'_{z0} = \sigma_{z0} - u$

$= 136 - 67 =$ **69 kPa**.

Solution (cont..):

- 5-m deep fill has been placed. These increases the vertical total stress:

$$\sigma_{zf} = \sigma_{z0} + \gamma_{fill} H_{fill}$$

$$= 136\text{kPa} + 19.5\text{x}5.0 = 234\ \text{kPa}$$

- **Initially the applied load** (fill) is carried entirely by the pore water. So the pore water pressure becomes:

$$u = u_h + u_e$$

$$= 67\text{kPa} + 19.5\text{x}5$$

$$= 165\text{kPa}$$

Solution (cont…)

- But the **vertical effective stress remain unchanged**,

σ'_z = σ_z- u (ie σ_{zf} -u)

=234 – 165

=**69 kPa**

- As some of the pore water drains away, soil element consolidates and $\Delta\sigma_z$ **is gradually transferred from the pore water to the solids.**
- After sufficient long time, u_e =0 and consolidation complete.

u = u_h + u_e = 67kPa + 0 =**67kPa**

σ'_z = σ_z- u

=234 – 67 = **167 kPa (Answer).**

What we are going to learn today?

- **What is Consolidation Test Sample?**
- **Test Procedures**
- **Loading Sequence**
- **Methods of presenting test result**
- **Plastic and elastic deformation**
- **Pre-consolidation Stress**

Consolidation Test Sample

- Tests are usually performed on **a high quality *undisturbed* samples (natural)**, of soft to medium clays and tests results are reliable.

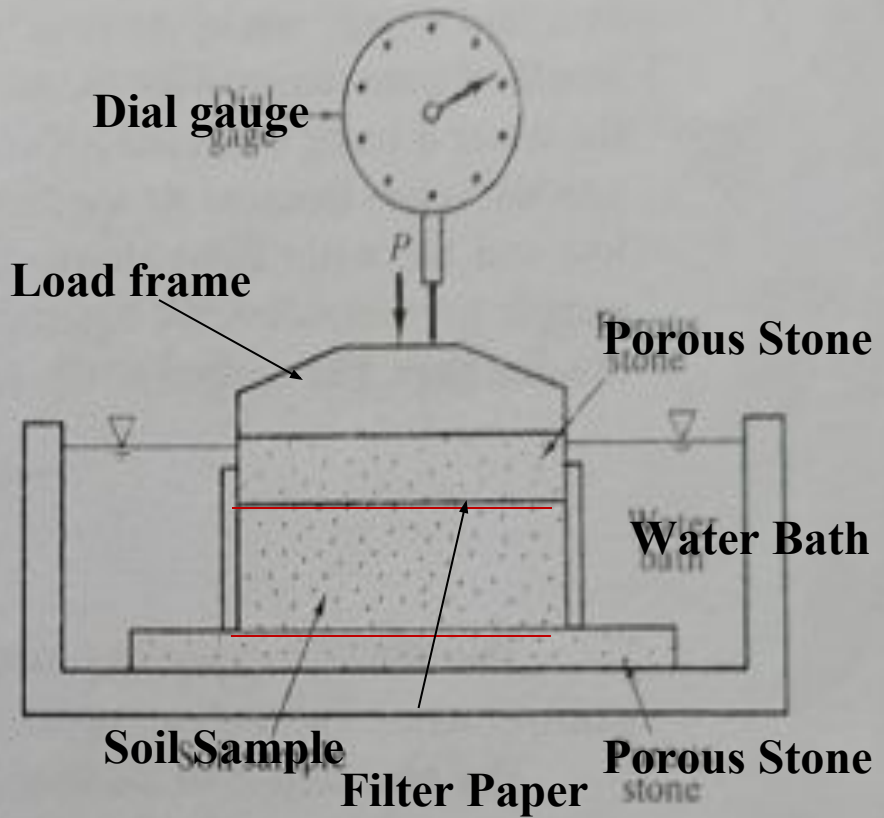
- It is virtually **impossible to obtain** high quality undisturbed samples and thereby **uses empirical correlations /in-situ tests** to asses the stress-strain properties.

- It is important for samples that were **saturated in the field** to remain so during storage and testing.

- Sometimes engineers need to evaluate the consolidation characteristics of **proposed compacted fills**, and do so by **performing consolidation tests** on **samples that has been remolded and compacted in the laboratory.**

Consolidation Test in the laboratory





Components

Specimen Ring:

- **Soil specimen**, which has the shape of an upright cylinder, is **placed in the consolidometer, and surrounded** by a brass or stainless **ring**.

Purpose of Rings:

-To maintain zero horizontal strain, producing one-dimensional consolidation.





Test Procedure

Porous Stones:

- **Porous stones** are placed above and below the specimen, which is **strong enough** to carry the applied loads and **porous enough** to allow water to pass through freely.

Filter Papers:

- Placed on top and bottom of soil specimen of specimen ring.

Water Bath:

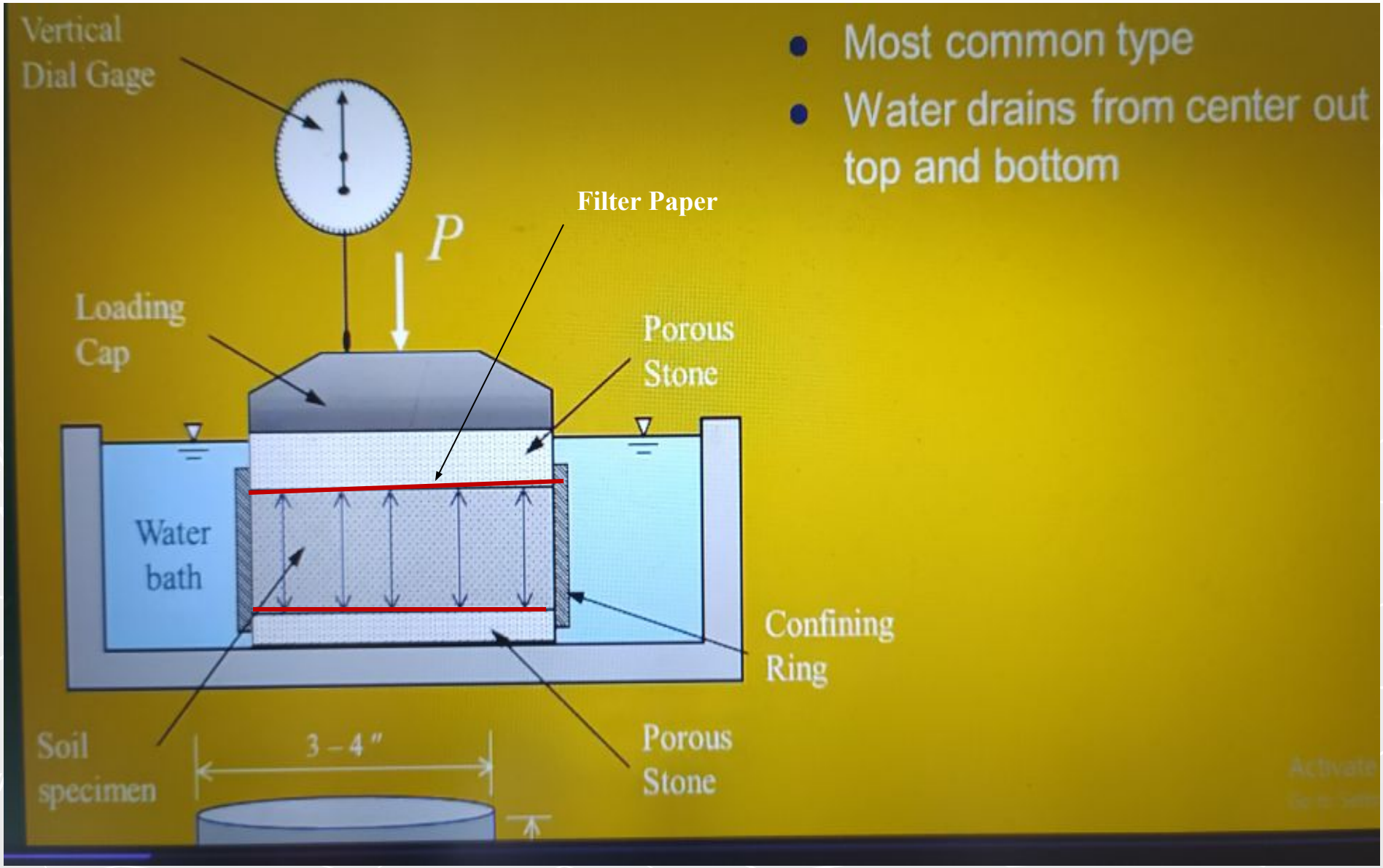
- Specimen, rings and porous stones are **submerged in a water bath**, to keep the soil saturated.

Device for Measuring Deformation:

- **A Dial gauge or device** is placed above the specimen to measure its compression as the test progresses.
- **Loading Cap:**
- **Loading Device:**



1-D Consolidation





Test procedure (cont…)

Loading Sequence

Step 1.

- **Test begins** by applying a vertical load, P, which produces a vertical effective stress, σ'_z.

$$\sigma'_z = \frac{P}{A} - u$$

Where, σ'_z = vertical effective stress

P= applied load

A= x-sectional area of whole specimen

u = pore water pressure inside the specimen.

- Water bath barely cover the specimen, **so u is very small** compares to σ'_z and thus may be ignored.

Test procedure (cont…)

- **Specimen is allowed to consolidate,** may require several hours or more.
- Completion of consolidation is determined by **monitoring the dial gauge. Vertical strain** $\in_z$, upon completion of consolidation is:

$$\in_z = \frac{change\ in\ dial\ gauge\ reading}{initial\ height\ of\ sample}$$

$$\varepsilon = \frac{\Delta L}{L_0}$$

where

- ε strain
- ΔL total elongation [m]
- L_0 original length [m]

Now, we have **1st data point** $(\sigma'_z, \in_z)$.

Step 2:

- **Increase the normal load** to some higher value and allow the soil to consolidate again, thus obtaining **2nd data point (σ'_z, $\in_z$).**
- **Process continues** until desired peak vertical stress is reached.
- From this loading sequence, **curve ABC** is obtained.

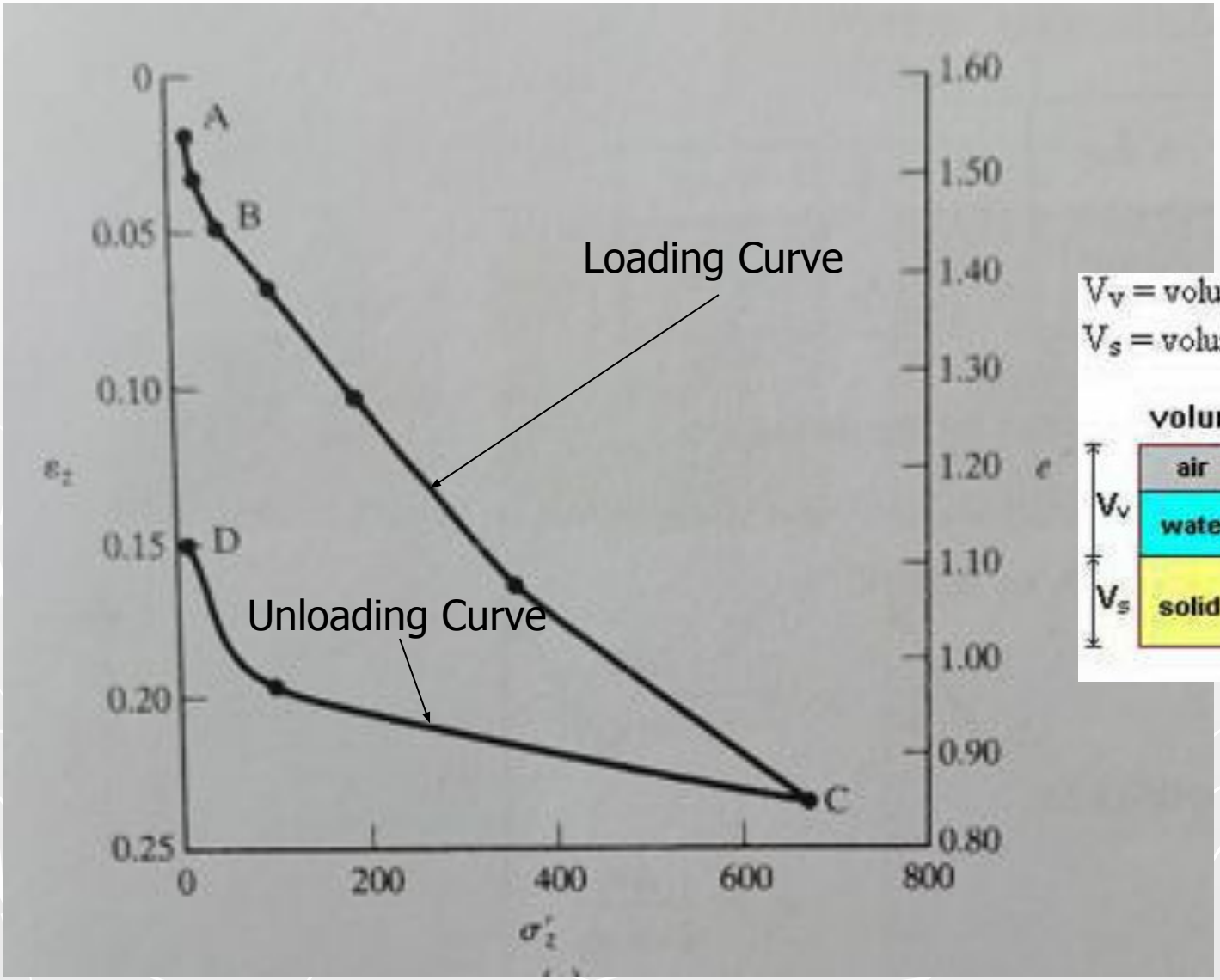
Unloading sequence:

- Now, **incrementally unload** the sample and allow it to rebound, thus producing the **unloading curve CD** (Figure).

- **Stress-strain curve for soil is decidedly non-linear** when plotted in arithmetic space.

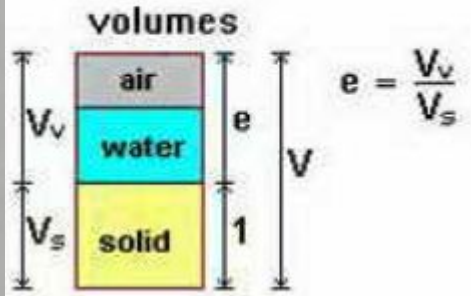
- But, when **presented on a semi-logarithmic plot** (Figure), the same data are much easier to interpret.

Figure: Result of laboratory consolidation test- data plotted on arithmetic scale. The initial void ratio, e_0 is 1.60.



V_v = volume of voids

V_s = volume of solid grains.



- In **semi logarithmic plot space**, the **stress-strain curve has three distinct segments** and each is nearly linear.

- Segment **AB** is known as ***reloading curve*** or ***recompression curve,*** ***BC*** is the ***virgin curve,*** and **CD** is the ***unloading curve*** or ***rebound curve***.

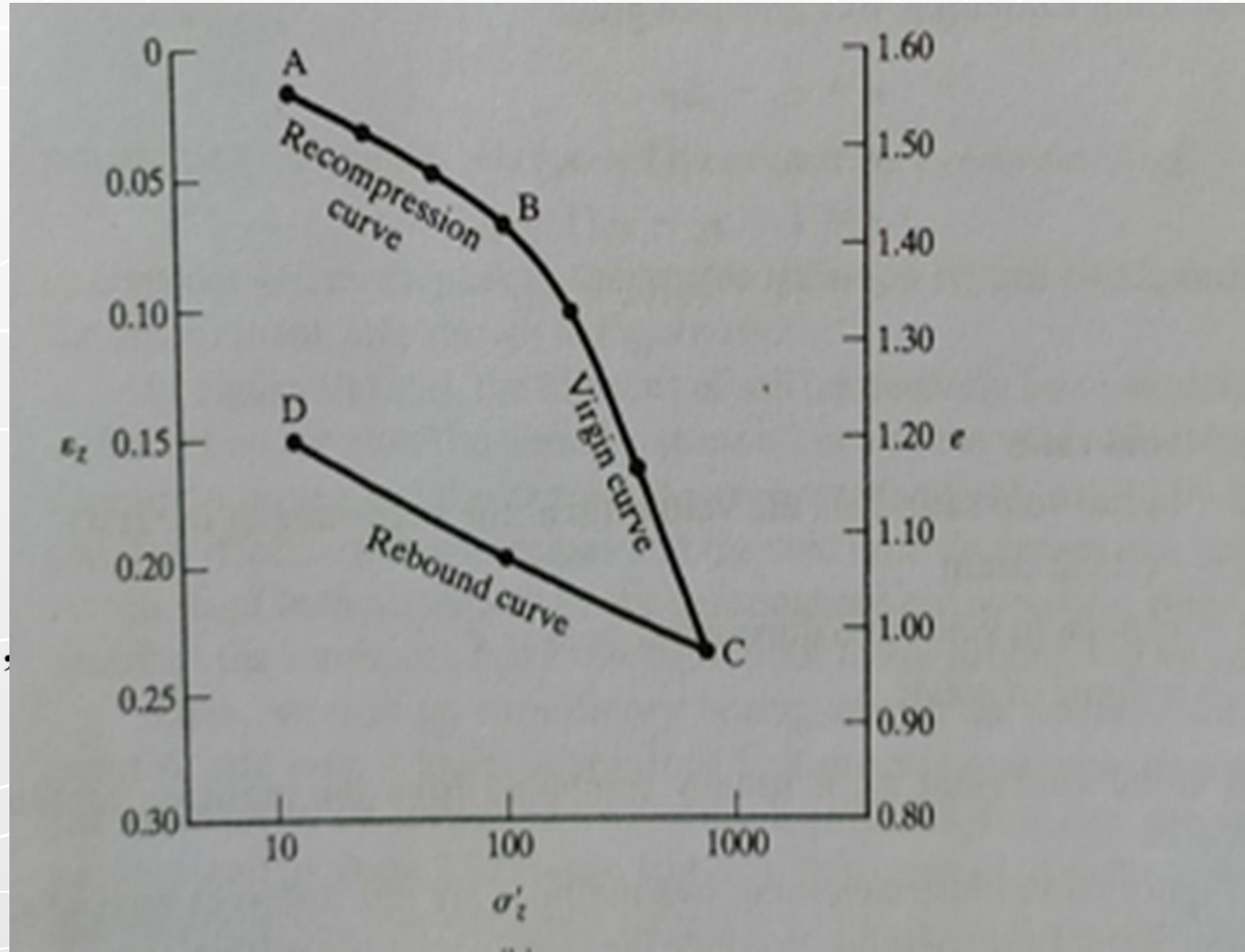


Figure: Result of laboratory consolidation test-data plotted on semi-logarithmic scale. Initial void ratio, ***e_0* is 1.60**.

Methods of presenting consolidation test results:

Two different methods of presenting consolidation test results, could be presented in either form or both..

A strain plot, 1st method:

- **Plot of $\in_z$ versus log σ'_z**, and thus a **direct representation of the data** obtained in the lab.
- **Most straight forward approach**, because the purpose of a consolidation test is to measure the stress-strain properties of soils.

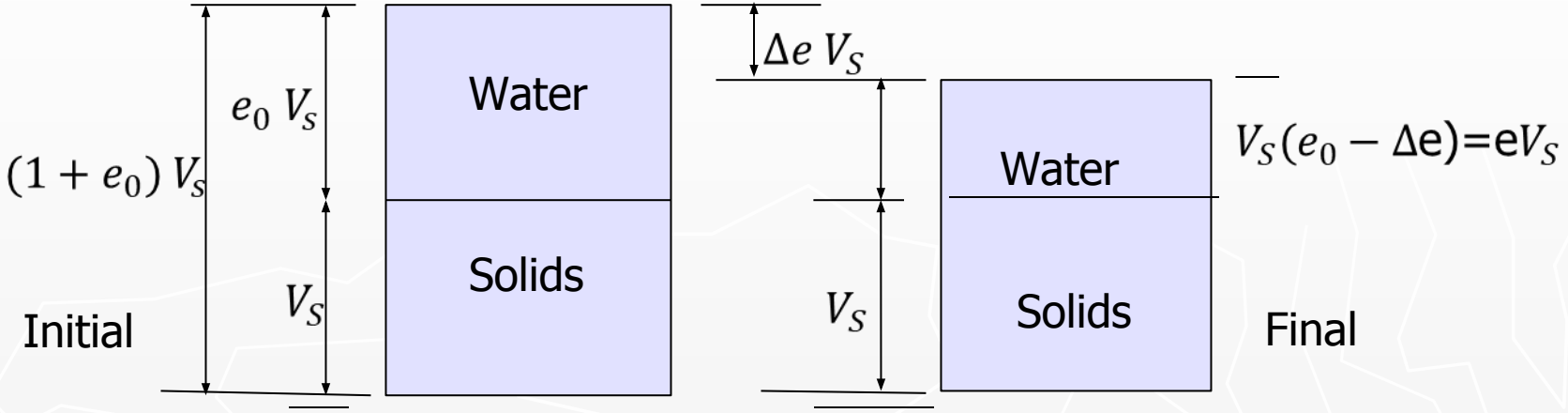
A void ratio plot, 2nd method:

- **Plot of void ratio e versus log σ'_z**, and **not a direct representation of the data obtained in the lab.**
- Method is **used by Terzaghi**, presumably **because**, it emphasizes the **reduction in void size** that occurs during consolidation.

To compute the void ratio at various stages of the test, **develop an**

Derivation of an equation that relates void ratio with strain

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



$$eV_S = e_0\, V_s - \Delta eV_S \quad \text{---------- (1)}$$

$$\epsilon_z = \frac{\Delta eV_S}{(1+e_0)\, V_s}$$

$$= \frac{\Delta e}{(1+e_0)} \quad \text{---------- (2)}$$

$$\varepsilon = \frac{\Delta L}{L_0}$$

where

- ε strain
- ΔL total elongation [m]
- L_0 original length [m]

Combining the equation (1) and (2),

$$e = e_0 - \Delta e$$

$$= e_0 - \epsilon_z\,(1+ e_0)$$

$$= 1+ e_0 - \epsilon_z\,(1+ e_0) -1$$

$$= (1 - \epsilon_z)\,(1 + e_0) - 1 \quad \text{---------- (3)}$$

Where,

e = void ratio

e_0= initial void ratio (ie. void ratio at beginning of the test).

$\in_z$ = vertical strain

Δe = change in void ratio during test= e_0 -e

V_S = volume of solids

- Initial void ratio, e_0, is usually computed from the moisture content using,

$$S = \frac{wG_s}{e} \times 100\%$$

Plastic and Elastic Deformation:



Question: Define plastic and elastic deformation.

Plastic deformation:

- All materials deform when subjected to an applied load.
- If all this **deformation** **is retained when the load is released**, it is said to have experienced *plastic deformation.*
- Example: **bending of an copper wire**.

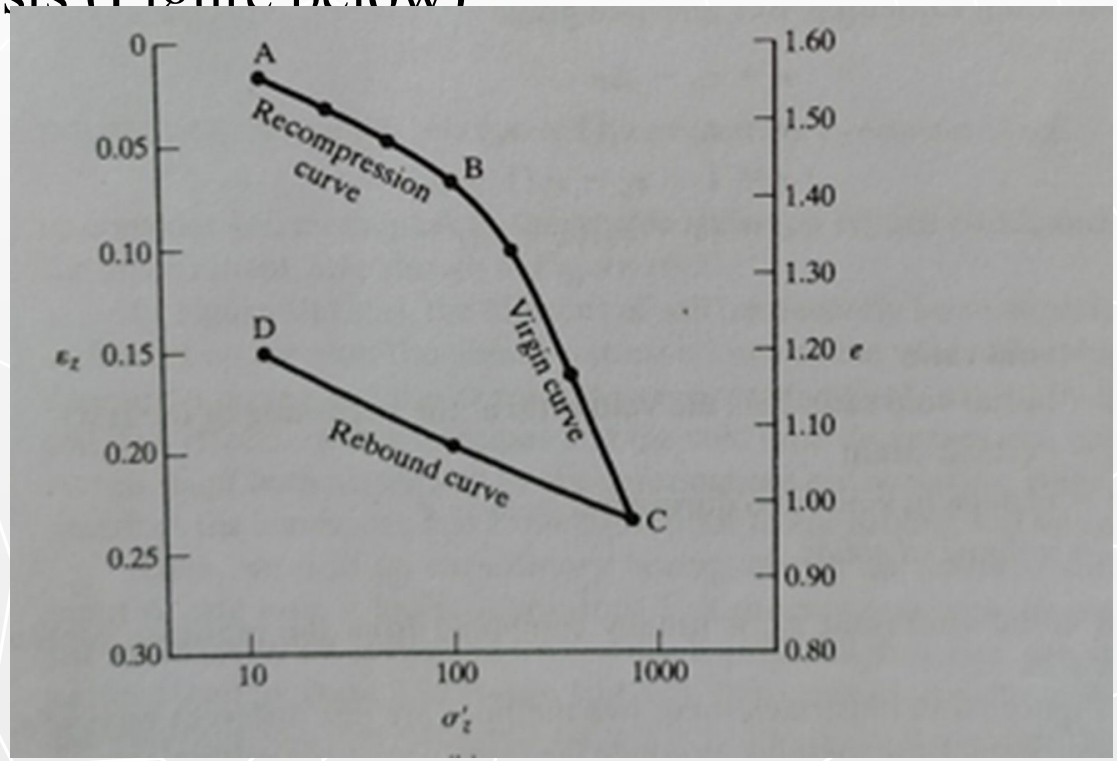


Elastic deformation:

- All materials deform when subjected to an applied load.
- If the **material** **return to its original size and shape when the load is released,** it is said to have experienced *Elastic deformation.*
- Example: bending of a rubber hose.

Question: Describe the plastic and elastic deformation of soils in the results of laboratory consolidation test.

- **Soil exhibits both plastic and elastic deformations**, this is why we see two slopes in the loading and unloading curves in the results of laboratory consolidation tests (Figure below)



Plastic and Elastic Deformation of soils under Applied Load:

Question: Explain the plastic and elastic deformations of soil under applied load.

To understand the plastic and elastic deformations of soil under applied load: Let us consider **soil element A** shown in the figure and **consolidation data** for this element.

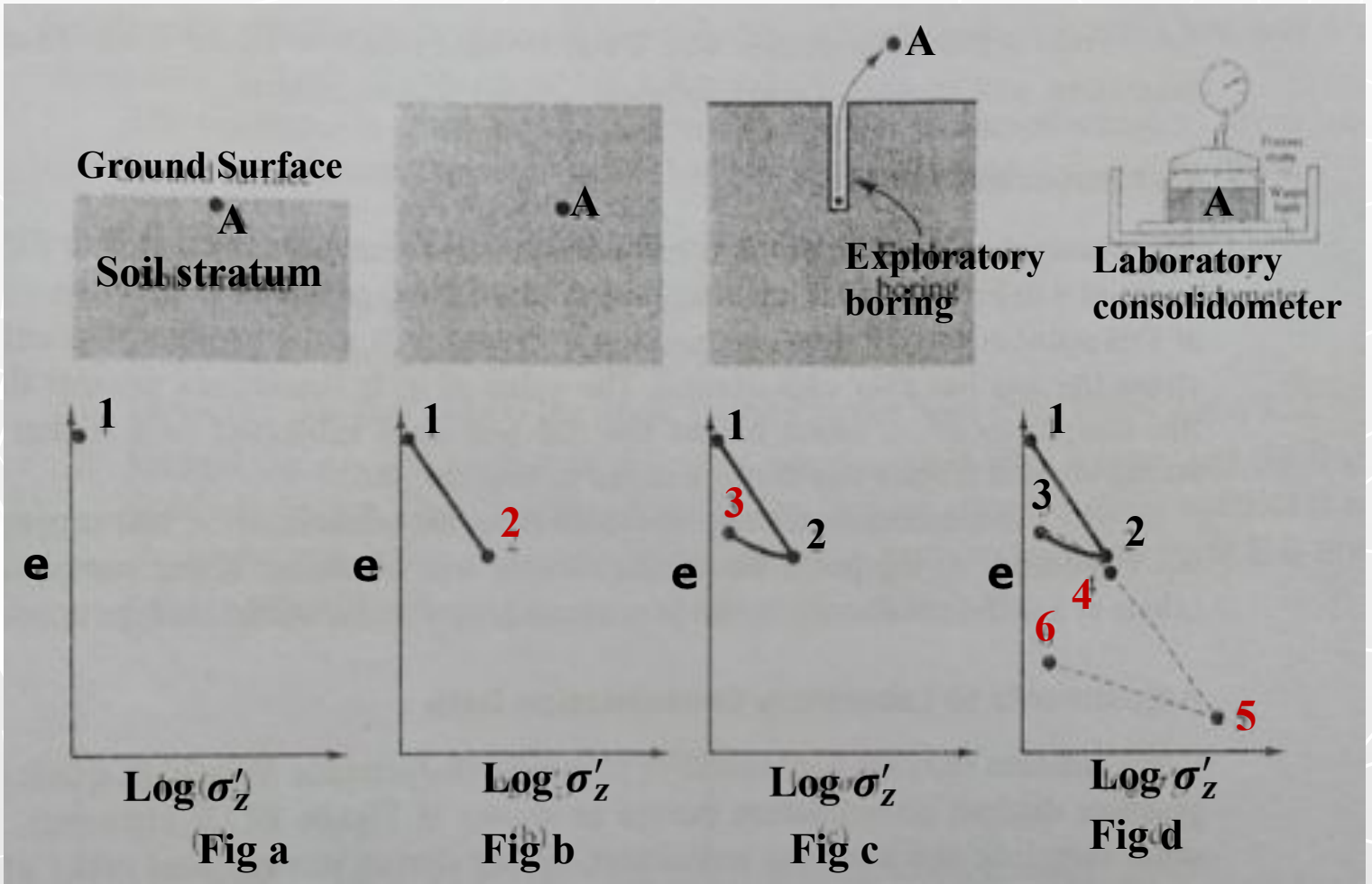


Figure (a):

- **Element of soil A**, has **recently been deposited** and is described by point 1 on the plot.
- Effective stress σ'_z, **is low** and the void ratio **e, is high**.

Figure (b):

- **Additional deposition occurs** and the element A, becomes progressively buried by the newly deposited soils.
- Effective stress σ'_z, **increases** and the void ratio **e, decreases (ie consolidation occurs)**.
- At this stage, **both plastic and elastic deformations are occurring.**
- **Point 2**, **describes the conditions** that **existed just prior to our drilling and sampling effort.**

Figure (c):

- We **drill an exploratory boring**, obtain an undisturbed sample from element A, and take into the laboratory.

- This **process removes the overburden stress**, so he **effective stress drops** and the **samples expands** slightly (ie. the **void ratio e increases**) as described by **Point 3**.

- **This expansion** reflects the **elastic portion** of the compression that occurred naturally in the field.

- Although, there has been **some elastic rebound**, **most of the compression was plastic**, so the unloading **curve 2-3 is much flatter** than the loading **curve 1-2.**

- Sample is reloaded in the lab, at point 3.

- **Curve 3-4** is nearly parallel to **curve 1-2** and **reflects elastic compression only**.

- Effective stressσ'_z, **is less than the maximum past effective stress,** so no new plastic deformation occurs.

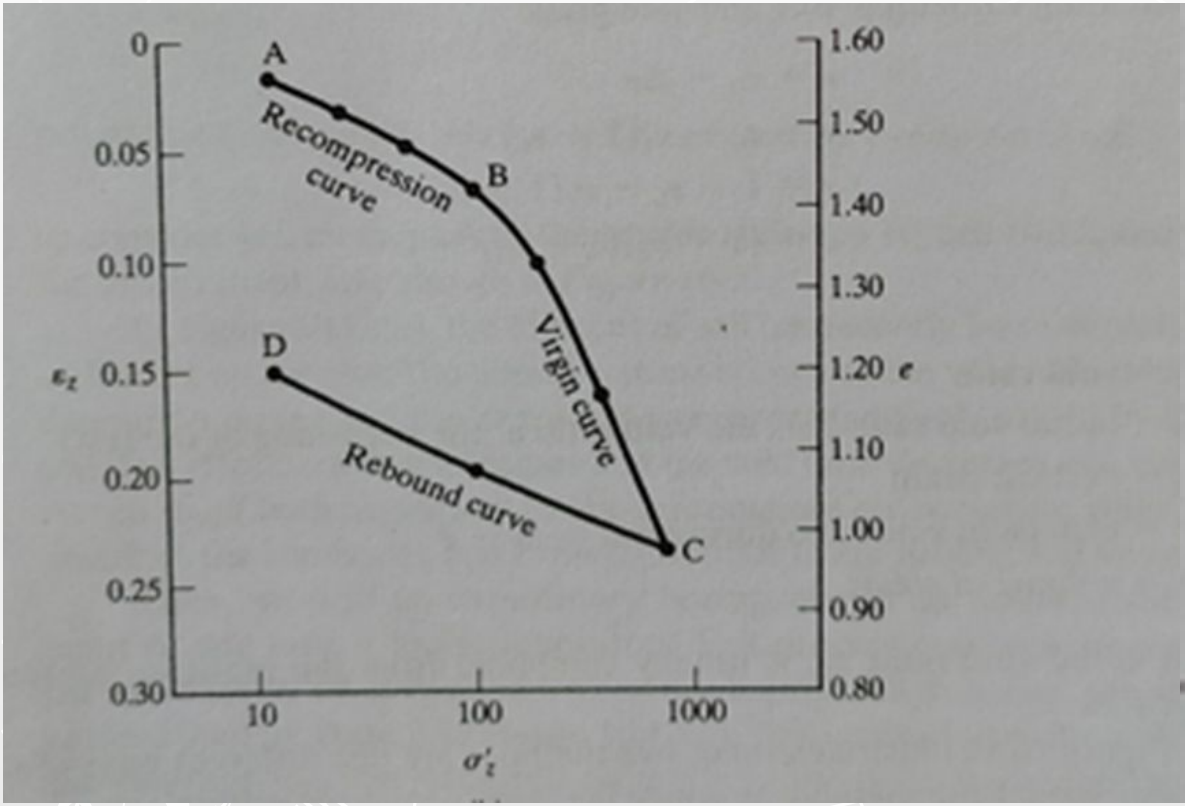
- **When the curve reaches Point 4**, its slope suddenly changes, and curve **4-5 reflects new** plastic deformations, which occur only, when the σ'_z, **is higher than ever before**. **Curve 4-5** is the virgin curve.

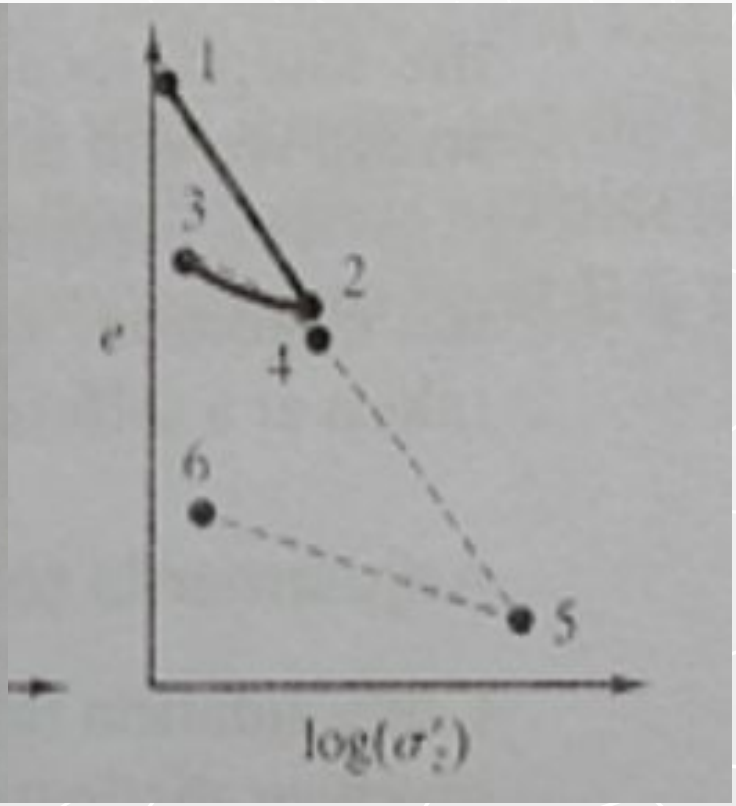
- Finally, when unload the specimen in the lab and form **Curve 5-6,** is the unloading or rebound curve.

- **Curve 5-6** is nearly parallel to **curves 2-3 and 2-3** and reflects the elastic component only.

Pre-consolidation Stress:

- Point where the **slope of the consolidation curve changes** (i.e. point B or Point 4) is an important event in the consolidation process.





Pre-consolidation Stress (cont..)

- Stress at this point is called the ***pre-consolidation stress*** σ'_c.
- It is the **greatest vertical effective stress** the soil has ever experienced.
- Value of $\sigma'_c > \sigma'_{z0}$ at the sample location, which mean the soil was once subjected to a higher effective stress.
- **Pre-consolidation stress** obtained from the consolidation test **represents only the conditions of soil** at that point.
- If the sample has been taken **at different elevation**, the pre-consolidation stress would change accordingly.

What we have learned today?

- **What is Consolidation Test?**
- **Test Procedures**
- **Loading Sequence**
- **Methods of presenting test result**
- **Plastic and elastic deformation**
- **Pre-consolidation Stress**

Thank you