One-dimensional Consolidation and Oedometer Test

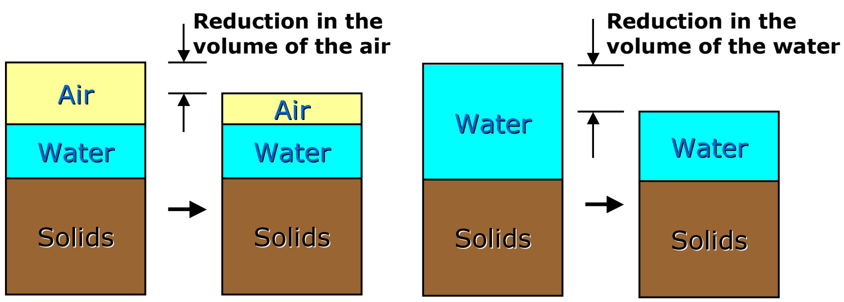
Lecture No. 12
October 24, 2002

Settlement of a Soil Layer

- The settlement is defined as the **compression** of a soil layer due to the **loading applied** at or near its top surface.
- The total settlement of a soil layer consists of three parts:
  - Immediate or **Elastic** Compression
  - Compression due to **Primary Consolidation**
  - Compression due to **Secondary Consolidation**
- The immediate or **elastic** compression can be calculated using the **elastic theory** if the elastic modulus of the soil layer is known.
- In this topic, we will learn the **consolidation** theory that is used to estimate the compression due to primary and secondary consolidation.

What is Consolidation?

- The process of consolidation is often confused with the process of compaction.
- The difference between consolidation and compaction can be appreciated using three-phase diagrams as shown below:



Compaction

Consolidation

What is Consolidation? (Continued..)

- **Compaction** increases the density of an unsaturated soil by **reducing the volume of air** in the voids.
- **Consolidation** is a **time-related** process of increasing the density of a saturated soil by **draining some of the water** out of the voids.
- **Consolidation** is generally related to **fine-grained** soils such as silts and clays.
- **Coarse-grained** soils (sands and gravels) also undergo consolidation but at **a much faster rate** due to their **high permeability**.
- **Saturated clays** consolidate at **a much slower rate** due to their **low permeability**.

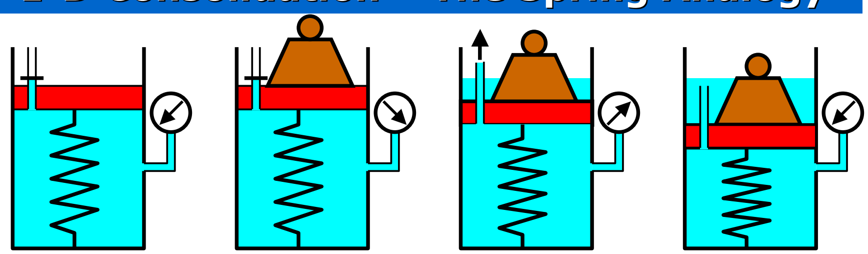
The Need for Consolidation Theory

- Consolidation theory is required for the prediction of both the **magnitude** and the **rate** of consolidation **settlements** to ensure the serviceability of structures founded on a compressible soil layer.
- **Differential settlements** that can lead to structural failures due to tilting should be avoided. Otherwise, you'll need extreme measures to save your structure !

One-dimensional Consolidation

- Since water can flow out of a saturated soil sample in **any direction**, the process of consolidation is essentially **three-dimensional**.
- However, in most field situations, water will not be able to flow out of the soil by flowing horizontally because of the vast expanse of the soil in horizontal direction.
- Therefore, the direction of flow of water is primarily **vertical** or **one-dimensional**.
- As a result, the soil layer undergoes **one-dimensional** or **1-D consolidation** settlement in the **vertical** direction.

1-D Consolidation – The Spring Analogy

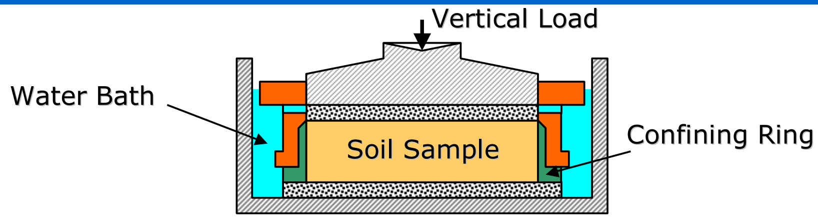


Initial Condition	Time t = 0	Time $t = t_1$	Time $t = t_{final}$
Valve Closed	Valve Closed	Valve Open	Valve Open
No loading on the piston	Loading on the piston	Water flows out	No water flow
Pressure gauge at zero	Pressure gauge at maximum	Pressure reading drops	Pressure gauge at zero
		Spring takes some load and compresses; piston sinks	Spring takes all the load; maximum compression

The Spring Analogy (Continued..)

- The **spring** is analogous to the **soil skeleton**. The stiffer the spring, the less it will compress.
- Therefore, a **stiff** soil will undergo **less compression** than a soft soil.
- The **stiffness** of a soil influences the **magnitude** of its consolidation settlement.
- The **valve opening size** is analogous to the **permeability** of the soil. The smaller the opening, the longer it will take for the water to flow out and dissipate its pressure.
- Therefore, **consolidation** of a **fine-grained** soil takes **longer** to complete than that of a coarse-grained soil.
- **Permeability** of a soil influences the **rate** of its consolidation.

The Oedometer Test



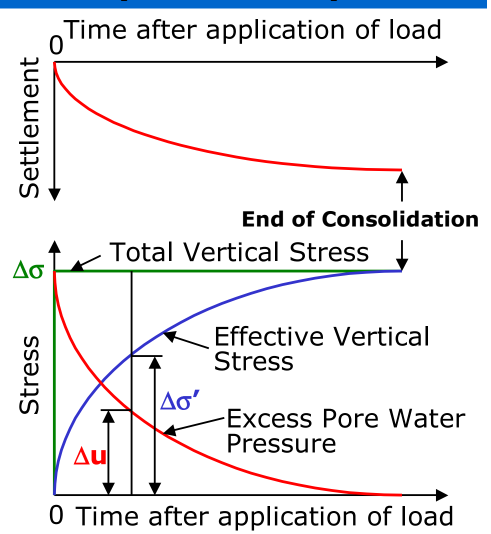
- The **oedometer test** is used to investigate the **1-D consolidation** behaviour of fine-grained soils.
- An **undisturbed** soil sample **20 mm** in height and **75 mm** in diameter is confined in a steel confining ring and immersed in a water bath.
- It is subjected to a **compressive stress** by applying a vertical load, which is assumed to act uniformly over the area of the soil sample.
- **Two-way drainage** is permitted through **porous disks** at the top and bottom as shown in the figure above.

The Oedometer Test (Continued..)

- The **vertical compression** of the soil sample is recorded using highly accurate **dial gauges**.
- Initially, **100 %** of the vertical load is taken by **pore water** because, due to low permeability of the soil sample, the pore water is **unable to flow out** of the voids quickly.
- Therefore, there is **very little compression** of the soil sample **immediately** after placing the vertical load.
- The **compression** of soil is possible only when there is an **increase in effective stress** which in turn requires that the **void ratio** of the soil be **reduced** by the **expulsion of pore water**.

The Oedometer Test (Continued..)

- After a few seconds, the pore water **begins to flow out** of the voids.
- This results in a **decrease** in **pore water pressure** and **void ratio** of the soil sample and an **increase** in **effective stress**.
- As a result, the soil sample **settles** as shown in the figure.



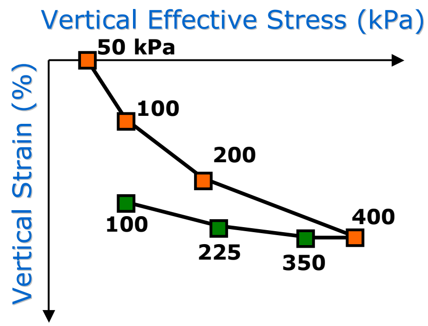
$\Delta\sigma = \Delta\sigma' + \Delta u$

The Oedometer Test (Continued..)

- Several increments of vertical stress are applied in an oedometer test usually by **doubling the previous increment**.
- For example, after the completion of consolidation for the **first** increment under a vertical stress of **50 kPa**, another **50 kPa** of vertical stress is applied so that the vertical stress during the **second** increment is **100 kPa**.
- For the **third** increment, another **100 kPa** of vertical stress is applied so that the vertical stress during the **third** increment is **200 kPa**.
- For each increment, the **final settlement** of the soil sample as well as the **time taken** to reach the **final settlement** is recorded.

The Oedometer Test (Continued..)

- The end points from a number of loading and unloading increments of an oedometer test may be plotted as a conventional stress-strain curve as shown in the figure on the right.

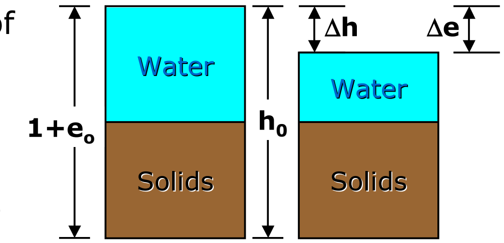


- The increment of vertical strain $\Delta\varepsilon_v$ for each loading increment is given by: $\Delta\varepsilon_v = \Delta s_{ult}/h_0$

  where Δs_{ult} is the final settlement for the loading increment (i.e. the change in sample height) and h_0 is the initial sample height.

The Oedometer Test (Continued..)

- Since the settlement of the soil is only due to change in void ratio, the vertical strain $\Delta\varepsilon_v$ can be expressed in terms of the void ratio of the soil sample at different stages of the test.

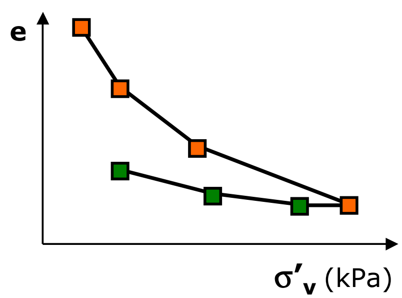


$$\Delta\varepsilon_v = \frac{\Delta h}{h_0} = \frac{\Delta e}{1+e_0}$$

- In the above equation, Δ**e** is the change in void ratio due to the loading increment and $\mathbf{e_0}$ is the void ratio of the soil sample before the application of the loading increment.

The Oedometer Test (Continued..)

- Since the void ratio of the soil sample at different stages of an oedometer test can be estimated using the equation on Page 14, it is customary to plot the results in terms of vertical effective stress σ'_v and void ratio **e** as shown in the figure on the right.

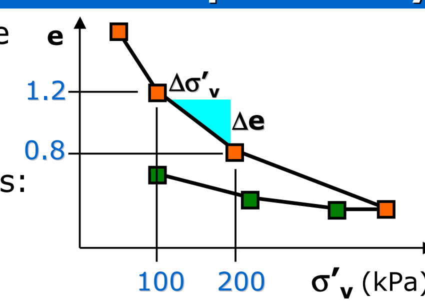


- The nature of the graph is not affected by the change in the vertical axis.

The Coefficient of Volume Compressibility

- The coefficient of volume compressibility $\mathbf{m_v}$ is defined as the ratio of volumetric strain over change in effective stress:

$$m_v = \frac{\Delta\varepsilon_v}{\Delta\sigma'_v} = \frac{\Delta e}{(1+e_0)\Delta\sigma'_v}$$



- The units for $\mathbf{m_v}$ are the inverse of pressure, i.e. $\mathbf{m^2/kN}$ and its value depends on the stress range over which it is calculated.
- For the second loading increment shown in the figure above:

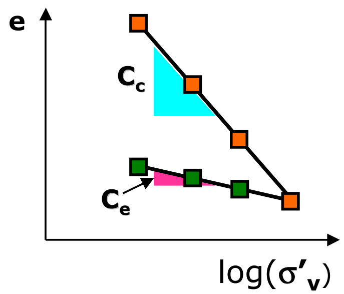
$$m_v = \frac{(1.2 - 0.8)}{(1+1.2)(200-100)} = 0.00182\ m^2/kN$$

Compression and Expansion Indices

- The **e-σ′$_v$** curve becomes almost linear if σ′$_v$ is plotted on a **log scale** as shown in the figure on the right.
- The slope of the loading curve is called the **Compression Index C_c** and is dimensionless. It is defined as:

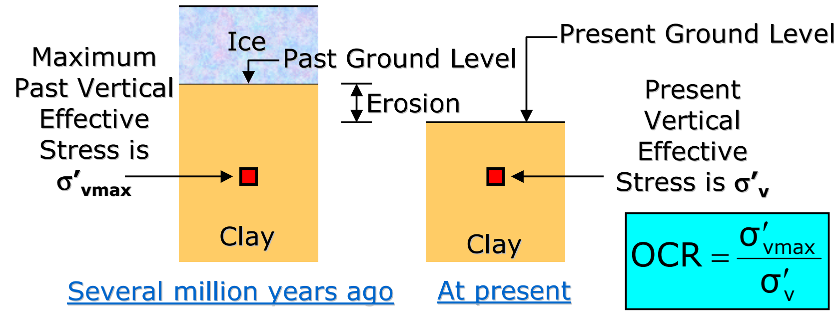
$$C_c = -\frac{e_1 - e_0}{\log(\sigma'_{v1}/\sigma'_{v0})}$$

- The negative sign is used because the void ratio **decreases** when the effective stress is **increased**.



- The slope of the unloading curve is called the **Expansion Index C_e** and is calculated using the same procedure.

Overconsolidation Ratio (OCR)



$$OCR = \frac{\sigma'_{vmax}}{\sigma'_v}$$

- **OCR** is defined as the ratio of **maximum past vertical effective stress** (σ′$_{vmax}$) over **present vertical effective stress** (σ′$_v$).
- The maximum past vertical effective stress is also called the **preconsolidation pressure** (σ′$_c$).

Normally Consolidated (NC) and Overconsolidated (OC) Soils

- A soil that **has never experienced** a vertical effective stress that was greater than its present vertical effective stress is called a **normally consolidated** (**NC**) soil.
- The OCR for an NC soil is **equal to 1**.
- Most NC soils have **fairly low** shear strength.
- A soil that **has experienced** a vertical effective stress that was greater than its present vertical effective stress is called an **overconsolidated** (**OC**) soil.
- The OCR for an OC soil is **greater than 1**.
- Most OC soils have **fairly high** shear strength.
- The OCR **cannot** have a value less than 1.

Preconsolidation Pressure

- An oedometer test of an undisturbed sample of an OC soil shows an e-log(σ′$_v$) curve as shown in the figure on the right.
- The slope of the e-log(σ′$_v$) curve is **fairly flat** until a vertical effective stress equal to the **preconsolidation pressure** (σ′$_c$) is reached.
- Beyond this point, the slope of the e-log(σ′$_v$) curve becomes **steeper**, i.e. the soil becomes more **compressible**.
- The preconsolidation pressure is like a **yield stress** for soil.
- This fact can be appreciated by rotating the curve by 90° in anti-clockwise direction. Doesn't this curve resemble a load-extension curve for a metal rod?