CONSOLIDATION

Consolidation is a process by which soils decrease in volume. According to Karl von Terzaghi "consolidation is any process which involves a decrease in water content of saturated soil without replacement of water by air." In general it is the process in which reduction in volume takes place by expulsion of water under long term static loads. It occurs when stress is applied to a soil that causes the soil particles to pack together more tightly, therefore reducing its bulk volume. When this occurs in a soil that is saturated with water, water will be squeezed out of the soil. The magnitude of consolidation can be predicted by many different methods. In the Classical Method, developed by Terzaghi, soils are tested with an oedometer test to determine their compression index. This can be used to predict the amount of consolidation.

Three Stages of 1D consolidation:

1. Initial Consolidation:

   When a load is applied to a partially saturated soil, a decrease in volume occurs due to expulsion and compression of air in the voids. A small decrease in volume occurs due to compression of solid particles. The reduction in volume of the soil just after the application of the load is known as initial consolidation or initial compression. For saturated soils, the initial consolidation is mainly due to compression of solid particles.

2. Primary consolidation

   After initial consolidation, further reduction in volume occurs due to expulsion of water from the voids. When a saturated soil is subjected to a pressure, initially all the applied pressure is taken up by water as an excess pore water pressure. A hydraulic gradient will develop and the water starts flowing out and a decrease in volume occurs. This reduction in volume is called as the primary consolidation of soil.

3. Secondary compression

   The reduction in volume continues at a very slow rate even after the excess hydrostatic pressure developed by the applied pressure is fully dissipated and the primary consolidation is complete. The additional reduction in the volume is called as the secondary consolidation. This is also called Secondary compression (Creep). “It is the change in volume of a fine grained soil due to rearrangement of soil particles (fabric) at constant effective stress”. The rate of secondary consolidation is very slow when compared with primary consolidation.
Consolidation analysis (spring analogy)

The process of consolidation is often explained with an idealized system composed of a spring, a container with a hole in its cover, and water. In this system, the spring represents the compressibility or the structure of the soil itself, and the water which fills the container represents the pore water in the soil.

1. The container is completely filled with water, and the hole is closed. (Fully saturated soil)
2. A load is applied onto the cover, while the hole is still unopened. At this stage, only the water resists the applied load. (Development of excess pore water pressure)
3. As soon as the hole is opened, water starts to drain out through the hole and the spring shortens. (Drainage of excess pore water pressure)
4. After some time, the drainage of water no longer occurs. Now, the spring alone resists the applied load. (Full dissipation of excess pore water pressure. End of consolidation)
Spring is analogous to effective stress (stress carried by soil skeleton)

Initially, the pore water takes up the change in total stress so effective stress does not change

As excess pore water pressure drains, the effective stress increases (skeleton takes up load)

Consolidation is complete when excess pressure dissipates and flow stops

So consolidation is TIME DEPENDENT because it is a pressure dissipation (flow) process!

Depends on hydraulic conductivity (k) and length of drainage path (H_{dr})

**Time dependency**

The time for consolidation to occur can be predicted. Sometimes consolidation can take years. This is especially true in saturated clays because their hydraulic conductivity is extremely low, and this causes the water to take an exceptionally long time to drain out of the soil. While drainage is occurring, the pore water pressure is greater than normal because it is carrying part of the applied stress (as opposed to the soil particles).

**Terzaghi’s 1D Consolidation Equation Testing**

**Assumptions:**

- The soil medium is completely saturated.
- The soil medium is isotropic and homogeneous.
- Darcy’s law is valid for flow of water.
- Flow is one dimensional in the vertical direction.
- The coefficient of permeability is constant.
- The coefficient of volume compressibility is constant.
- The increase in stress on the compressible soil deposit is constant.
- Soil particles and water are incompressible.
**One dimensional theory is based on the following hypothesis:**

1. The change in volume of soil is equal to volume of pore water expelled.
2. The volume of pore water expelled is equal to change in volume of voids.
3. Since compression is in one direction the change in volume is equal to change in height. The increase in vertical stress at any depth is equal to the decrease in excess pore water pressure at the depth

\[ \Delta \sigma' = \Delta u \]

This is Terzaghi’s one dimensional consolidation equation

\[ \frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial z^2} \]

This equation describes the variation of excess pore water pressure with time and depth.

**1-D consolidation test:**
- Undisturbed saturated soil (clay, silt) – representative of in-situ stratum
- Typical specimen size: h = 1", diam. = 2”-3”
- Specimen confined in rigid ring (no lateral deformation, “plane strain”)
- Drainage allowed on top and bottom via porous stones
- Apply increment of load and measure 1-D compression with time

**Theory:**

Consolidation of a saturated soil occurs due to expulsion of water under static, sustained load. The consolidation characteristics of soils are required to predict the magnitude and the rate of settlement. The following characteristics are obtained from the consolidation test.

Coefficient of compressibility,

\[ a_v = - \frac{\Delta e}{\Delta \sigma} \]

Coefficient of volume change

\[ m_v = \frac{-\Delta e}{1 + e} \left( \frac{1}{\Delta \sigma} \right) \]

\( \Delta e = \) Change in void ratio
\( \Delta \sigma = \) Change in applied pressure
\( e = \) Initial void ratio

It is used to find total settlement.
Compression Index

\[ C_c = \frac{-\Delta e}{\log \left( \frac{\sigma_o + \Delta \sigma}{\sigma_o} \right)} \]

Coefficient of consolidation

\[ C_v = \frac{n}{t} = \frac{k}{\gamma_w m_v} \]

\( K = \text{Co-efficient of permeability of soil} \)

\( \gamma_w = \text{Density of water} \)

**Unit:** cm²/sec, ft²/year

It is used to measure rate of settlement.

**Primary Consolidation**

** Settlement caused by structural loading \((S_p)\):**

\[ S_p = \frac{C_c H}{1 + e_0} \log \left( \frac{\sigma'_o + \Delta \sigma'}{\sigma'_o} \right) \]

**Assumptions**

1) All compression occurs due to change in void ratio
   a. i.e., the grains do not compress
   b. Thus, we can relate change in void ratio \((e)\) to change in volume

\[ e = \frac{V}{V_0} \text{ if } V \downarrow \text{ then } e \downarrow \]

2) All strains are vertical (1-D)

\[ \varepsilon = \frac{\Delta H}{H_0} = \frac{\Delta V}{V_t} \]

\[ \text{where } \Delta V = \Delta V_v \]

\[ \therefore \varepsilon = \frac{\Delta V_v}{V_t} = \frac{\Delta V_v}{V_v + V_s} = \frac{\Delta V_v}{V_v + \frac{V_s}{V_s}} = \frac{\Delta e}{1 + e_0} \]

\[ \varepsilon = \frac{\Delta e}{1 + e_0} \]

**Procedures**

1) Trimming
2) Specimen set up and initialization (seating load, \(s'v0\))
3) Apply an increment of vertical load \((\sigma'v = P/A)\)
4) Record DH with time, compute De with time
5) Monitor until volume change ceases (~24 h)
6) Repeat 3-5 to generate load-compression curve
**Limitation of 1D consolidation**

1. In the deviation of 1D equation the permeability (Kz) and coefficient of volume compressibility (mv) are assumed constant, but as consolidation progresses void spaces decrease and this results in decrease of permeability and therefore permeability is not constant. The coefficient of volume compressibility also changes with stress level. Therefore Cv is not constant.

2. The flow is assumed to be 1D but in reality flow is three dimensional.

3. The application of external load is assumed to produce excess pore water pressure over the entire soil stratum but in some cases the excess pore water pressure does not develop over the entire clay stratum.

**Normally Consolidated (NC):** Normally consolidated clay is one which had not been subjected to a pressure greater than the present exciting pressure.

**Overconsolidated Clay (OC):** The present overburden pressure is less than the soil has experienced in the past. The maximum effective past pressure is called the preconsolidation pressure ($\sigma_c$) or Maximum Past Pressure ($\sigma_{vm}$).

### DETERMINATION OF MAXIMUM PAST PRESSURE:

**Graphical Method (Casagrande, 1936)**

1. Visually identify point of minimum radius of curvature on e-log $\sigma^\prime$ curve (i.e. Point a).
2. Draw horizontal line from Point a (i.e. Line ab).
3. Draw Line ac tangent to Point a.
5. Project the straight line portion of curve to intersect gh on e-log$\sigma^\prime$ Line ad. This intersection (Point f) is the maximum past pressure (preconsolidation pressure).

### OVERCONSOLIDATION RATIO (OCR)

$$OCR = \frac{\sigma_c}{\sigma^\prime}$$

Where:
- $\sigma_c$ (a.k.a. $\sigma_{vm}$) = Preconsolidation Pressure (a.k.a Maximum Past Pressure).
- $\sigma^\prime$ = Present Effective Vertical Stress

**General Guidelines:**
- NC Soils: $1 \leq OCR \leq 2$
- OC Soils : $OCR > 2$

**Possible Causes of OC Soils:**
- Preloading (thick sediments, glacial ice); fluctuations of GWT, under draining, light ice/snow loads, desiccation above GWT, secondary compression.
Example 1: How long for 90% consolidation?

$U = 0.90$

From figure, $T = 0.848$

$T = \frac{c_v t}{(H_{dr})^2} = 0.848$

$t = \frac{(0.848)(H_{dr})^2}{c_v}$

$t = \frac{(0.848)(10)^2}{0.05 \text{ ft}^2 / \text{day}} = 1696 \text{ days}$

$t = 4.6 \text{ years}$
If $S_\infty = 4.0'$, how long for $2'$ of settlement?

$$U = \frac{S_t}{S_\infty} = \frac{2'}{4'} = 0.5 \quad (50\%)$$

From figure, $T = 0.196$

$$T = \frac{c_v t}{(H_{dr})^2} = 0.196$$

$$t = \frac{(0.196)(H_{dr})^2}{c_v}$$

$$t = \frac{(0.196)(10')^2}{0.05 \text{ ft}^2 \text{ / day}} = 394 \text{ days}$$

$$t = 1.1 \text{ years}$$

If bottom boundary is impervious, how long for $90\%$ consolidation?

$$U = 0.90$$

From figure, $T = 0.848$

$$T = \frac{c_v t}{(H_{dr})^2} = 0.848$$

$$t = \frac{(0.848)(H_{dr})^2}{c_v}$$

$$t = \frac{(0.848)(20')^2}{0.05 \text{ ft}^2 \text{ / day}} = 6784 \text{ days}$$

$$t = 18.6 \text{ years} !!!!!!$$
Example 2: Compute total consolidation settlement and time for 95% consolidation

\[ \sigma'_{i} = \sigma'_{p} \]

Analyze using Point A at midpoint of clay

\[ \sigma'_{A_i} = (100)(25) - (62.4)(25) = 940 \text{ psf} \]
\[ \sigma'_{A_f} = 940 + (100)(20) = 2940 \text{ psf} \]

\[ S_{\infty} = \Lambda H = \frac{C_{c}H}{1+e_{o}} \log \left( \frac{\sigma'_{A_f}}{\sigma'_{A_i}} \right) \]
\[ S_{\infty} = \frac{(0.4)(50')}{1+1.2} \log \left( \frac{2940}{940} \right) = 4.5' \]

Not given \( c_{v} \), so need to calculate...

\[ c_{v} = \frac{k}{m_{r}Y_{w}} \]

\[ m_{r} = \frac{d\sigma}{d\sigma'} = \frac{\Delta H}{H_{b}} = \frac{4.5}{200} = 4.5 \times 10^{-5} \text{ ft}^2 / \text{lb} \]

so

\[ c_{v} = \frac{(10^{-6} \text{ cm/s}) (1 \text{ ft} / 30.5 \text{ cm}) (86,400 \text{ s/day})}{(4.5 \times 10^{-5} \text{ ft}^2 / \text{lb}) (62.4 \text{ pcf})} = 1.009 \text{ ft}^2 / \text{day} \]

If \( U = 95\% \), \( T = 1.129 \)

\[ t = \frac{T (H_{b})^2}{c_{v}} = \frac{(1.129)(50')^2}{1.009 \text{ ft}^2 / \text{day}} = 7.7 \text{ years} \]

\[ S_{i} = \left( \frac{U}{S_{\infty}} \right) = (0.95)(4.5') = 4.28' \]