Period #15: Soil Compressibility and Consolidation (I)

A. Motivation and Overview

- Our objective is now to understand how soils compress or consolidate with time after loads are placed on them.

- This a question of great importance when designing:
  a) foundations for all types of structures;
  b) landfills;or
  c) virtually anyother system that rests on soil.

- In studying the consolidation of soils there are two basic issues to be addressed:

  1) Once a load is applied, **how much** settlement will occur? and
  2) On what **time scale** will the settlement occur?

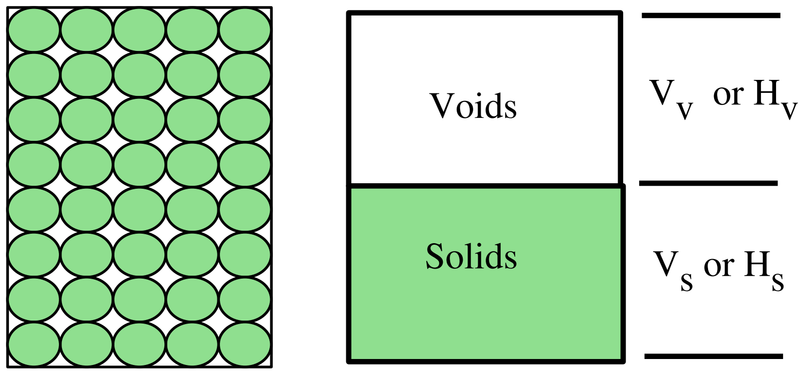
- A historic example of relevance is the Tower of Pisa.

  - In this case, the builders did not understand either:
    - how to compute soil settlements under structural loading; or
    - how to compute the time scale on which settlements would occur.

  - Consequently, over a time scale of centuries, the soil beneath this famous structure has developed very significant consolidation settlements. If unchecked, the structure would ultimately topple over.

B. Magnitude of Settlement/Consolidation in Soils

- Consider the following block diagram for a soil:



$$V_S + V_V = V \qquad H_S + H_V = H$$

$$V_V = eV_S \qquad H_V = eH_S$$

$$(1+e)V_S = V \qquad (1+e)H_S = H$$

$$V_S = V/(1+e) \qquad H_S = H/(1+e)$$

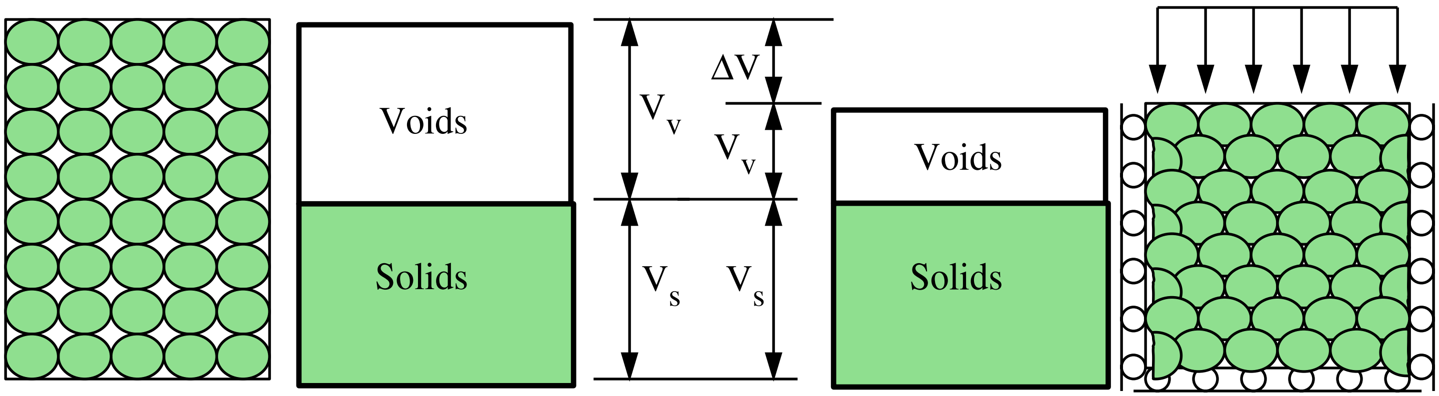
- For simplicity in treating the compression of soils, it isssumed that:

  a) the soil grains themselves are rigid and incompressible; and

  b) the change in volume of a soil is due to a re−arrangement of the soil grains, leading to a reduction of void volume.

- For most soils, these assumptions are quite valid.

∴ When a soil is subjected to compressive stresses, there will be a reduction of volume. Most of the volume reduction comes from a reduction in void volume, as shown below.



General Case:

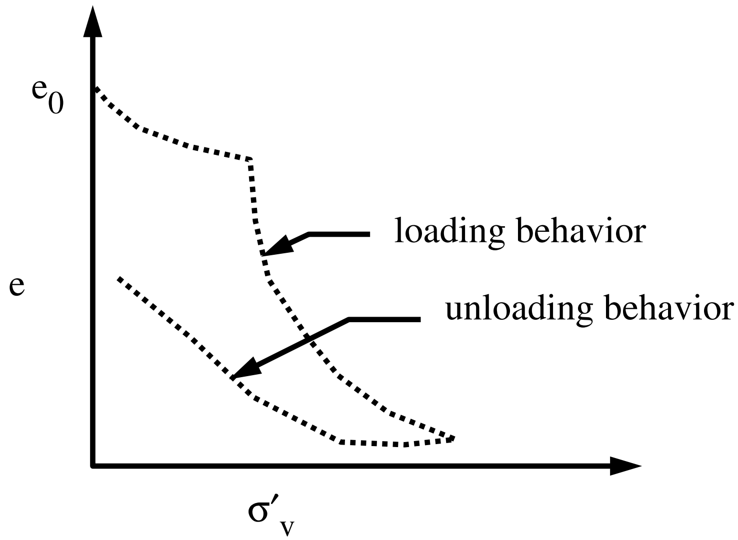
$$\Delta V = \Delta V_v + \Delta V_s$$
$$= \Delta(eV_s) + \Delta V_s$$
$$= (\Delta e)V_s + e\Delta V_s + \Delta V_s$$
$$= (\Delta e)V_s$$
$$\Delta V = \Delta e\, V_0/(1+e_0)$$

One–Dimensional Compression:

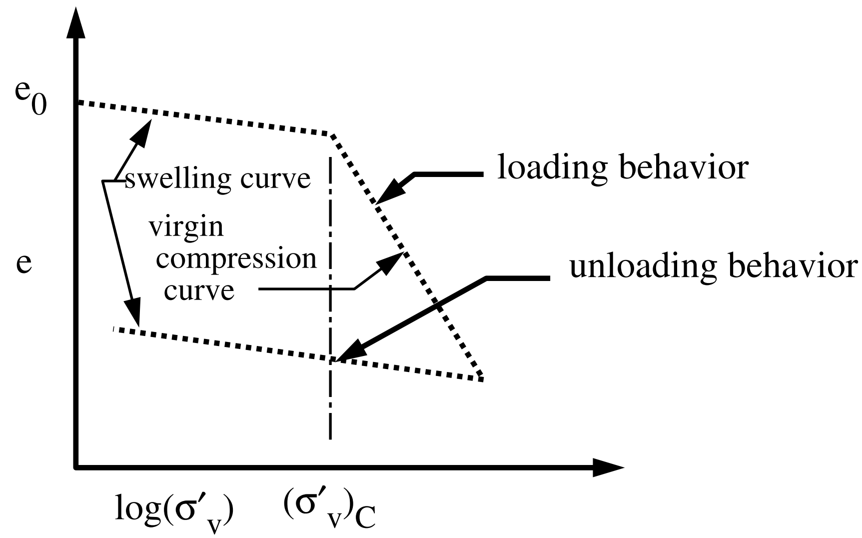
$$\Delta H = \Delta H_v + \Delta H_s$$
$$= \Delta(eH_s) + \Delta H_s$$
$$= (\Delta e)H_s + e\Delta H_s + \Delta H_s$$
$$= (\Delta e)H_s$$
$$\Delta H = \Delta e\, H_0/(1+e_0)$$

- Thus, changes in volume in soil are directly related to changes in the void ratio e.

- If the one–dimensional compression behavior of a soil were measured, the observed relationship between void ratio e and and σ'_v would be highly nonlinear (see Figure a below).
- However, if the same behavior were plotted on a log–linear scale, the response would appear more linear (see Figure b below).



a) Idealized e vs. σ'_v behavior of a soil.



b) Idealized e vs. $\log(\sigma'_v)$ behavior of a soil.

- Physically, $(\sigma_v')_c$ or p_c is the *maximum vertical effective stress* that the soil has ever seen in its preceding history. It is called the *pre–consolidation stress*.
- The dimensionless slope of the virgin compression curve is C_c and is called the *compression index.*
  Along the virgin compression curve, $\Delta e = -C_c \, \Delta\log(\sigma'_v)$
- The dimensionless slope of the swelling curve is C_s and is called the *swelling index.*
  Along the swelling curve, $\Delta e = -C_s \, \Delta\log(\sigma'_v)$

- If for a soil, $(\sigma'_v)_c > (\sigma'_v)$, then the soil is said to be *overconsolidated*, because in its history it has experienced a vertical effective stress larger than that which it presently experiences.

- If for a soil, $(\sigma'_v)_c = (\sigma'_v)$, then the soil is said to be *normally consolidated*, because it presently experiences the maximum vertical effective stress ever in its entire history.

- The consolidation ratio (OCR) for soils is defined as:

$$OCR \equiv (\sigma'_v)_c / \sigma'_v$$

  - over–consolidated (OC) soils have OCR > 1;
  - normally–consolidated (NC) soils have OCR = 1.

- Consolidation settlement of a soil layer undergoing 1–D compression under an applied loading of Δq is $\Delta H = \Delta e\, H_0/(1+e_0)$

  - For a *normally consolidated* soil the change in height of the layer is:

$$\Delta H = [H_0/(1+e_0)]\ C_c \log[\,((\sigma'_v)_0 + \Delta q)/ (\sigma'_v)_0\,]$$

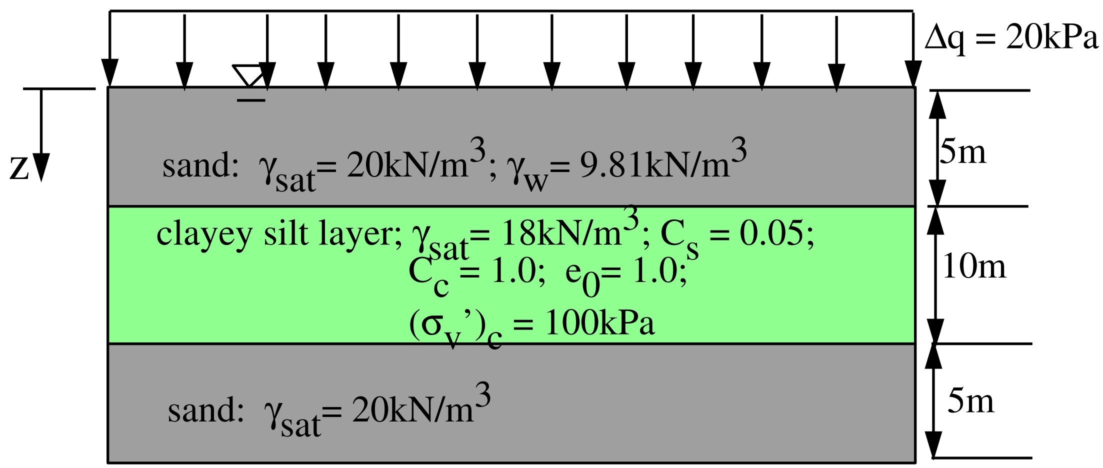
  - For an *over–consolidated* soil, the change in height is::

$$\Delta H = H_0/(1+e_0)\ \{C_s \log[\,(\sigma'_v)_c/ (\sigma'_v)_0\,] + C_c \log[\,((\sigma'_v)_0 + \Delta q)/ (\sigma_v')_0\,]\,\}$$

  - Note that $(\sigma'_v)_0$, $(\sigma'_v)_c$, and Δq are generally computed at the center of the layer in question.

Example Problem::

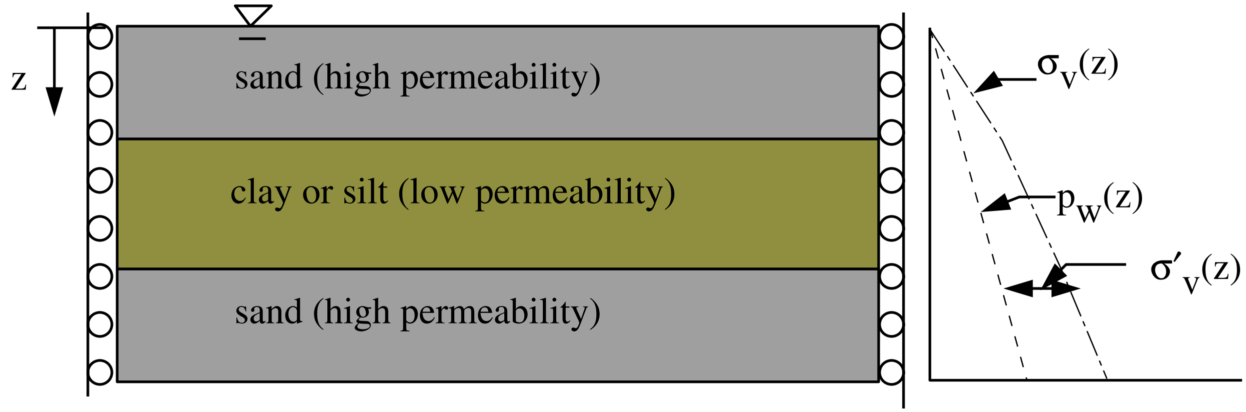
For the soil deposit shown, find the change in thickness of the clay layer due to the application of a load $\Delta q = 20\text{kPa}$ as shown:



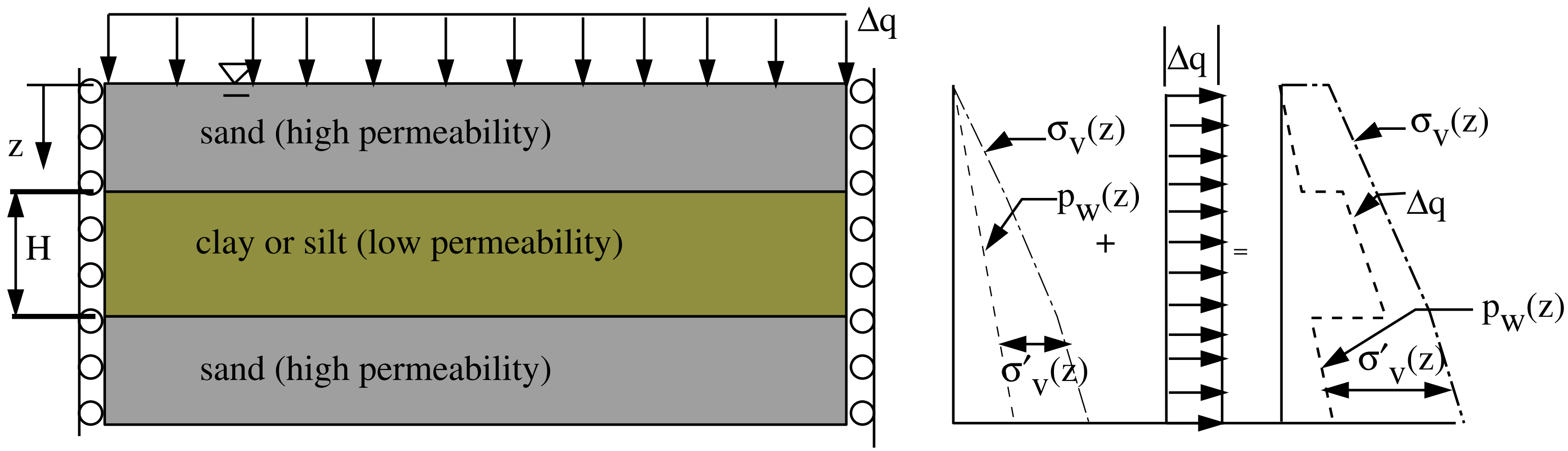
Solution:

B. Understanding Consolidation Rate Effects:

- Consider the soil deposit shown below.
  It is fully consolidated under its own weight, leading to an equilibrium distribution of $\sigma_v(z)$, $p_w(z)$, and $\sigma'_v(z)$ as shown.



- If the soil deposit is subjected to the loading shown, then **<u>shortly afterwards</u>**, the new distributions of $\sigma_v(z)$, $p_w(z)$, and $\sigma'_v(z)$ will be as shown.



- Interpretation: In the sand layers, the new load Δq is taken up by effective stresses.
  In the clay/silt layer, the load Δq is taken up by pore pressure.

- However, with passage of time:

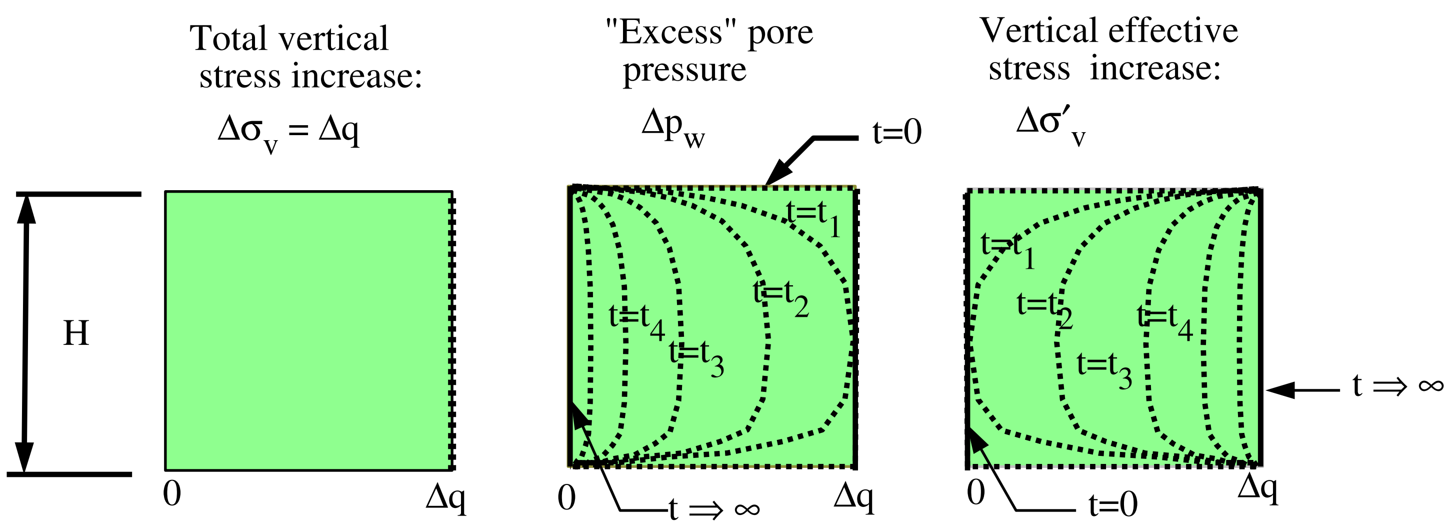
  a) the fluid in the silt/clay layer which is under excess pressure will drain into the sand layers above and below;

  b) as the fluid drains out, the fluid pressure in the silt/clay layer will drop;

  c) as this occurs, the increased vertical stress Δq in the silt/clay will be carried by effective stresses;

  d) as the stress increase Δq is transferred to the soil skeleton, the silt/clay layer will gradually compress. This is because the soil skeleton is usually much more compressible than water is.

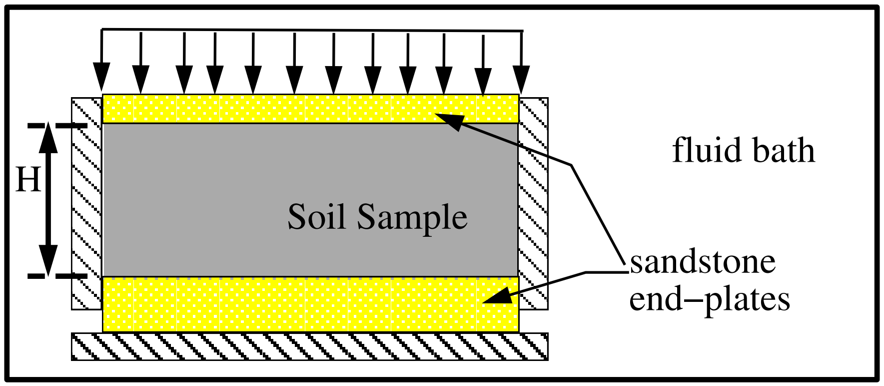
- Focusing on the vertical stresses in the clay layer as a function of time, the following would occur:



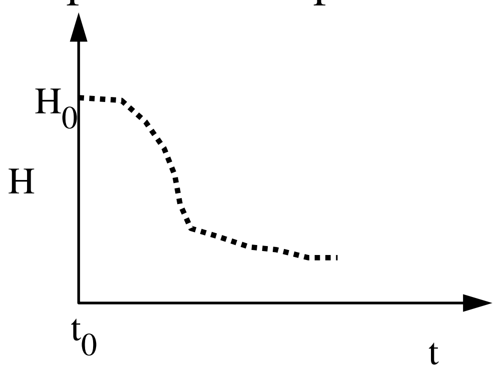
- Total vertical stress remains constant. But pore pressure decreases while effective stress increases.

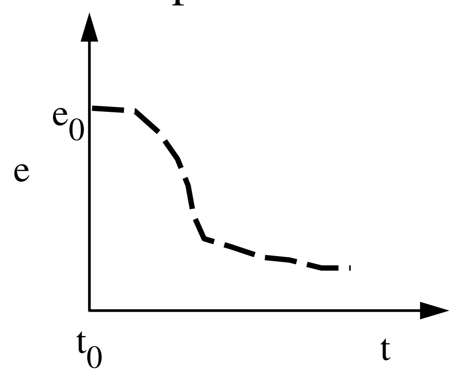
D. Measuring 1−D Consolidation Behavior in the Laboratory

Basic Apparatus: The Oedometer



- For a given increment of compressive vertical stress on the soil sample, time dependent compression of the soil sample is observed:

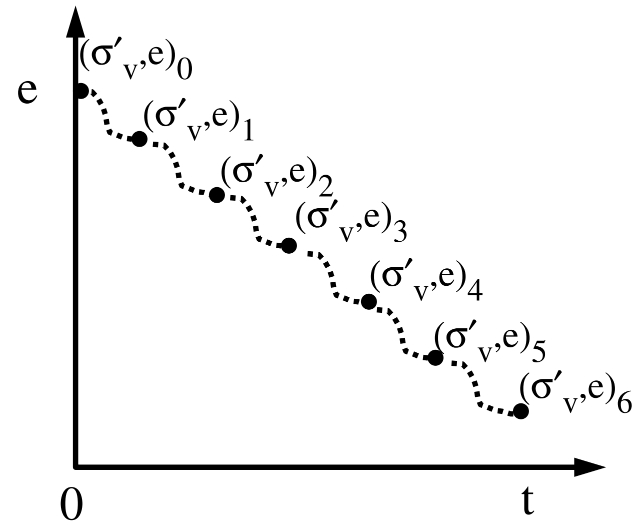




- A reduction in height H of the soil layer occurs as a functionof time, eventually reaching an equilibrium value. As H decreases, so does e.

Over *many loading increments*, one would see something like that below:

- That is, for each value of σ'_v, a corresponding equilibrium value of e is eventually achieved in the soil.



Procedure for Confined Compression Testing:

1) Mount soil specimen in oedometer and testing machine.

2) Increment total vertical stress σ_v.

3) Measure H(t), and wait for excess pore fluid pressure in the soil sample to diffuse.

4) When pore pressure diffusion is complete, measure the final change in height ΔH of the specimen;

5) Calculate the associated change in void ratio of the soil as: $\Delta e = \Delta H/H_s$

6) Return to Step #2 and repeat.

7) Upon completion of the test, plot e versus $\log(\sigma'_v)$