Module 6: Consolidation (part 1)

Luis Zambrano-Cruzatty, Ph.D.

Spring 2022

March 11, 2022

COURSE CONTENTS AND SCHEDULE

Department of
Civil and Environmental Engineering

THE UNIVERSITY OF MAINE

308 Boardman Hall
Orono, Maine 04469-5711
Tel: 207.581.1277
Fax: 207.581.3888
Email: luis.zambranocruzatty@maine.edu

Tentative schedule

Day	Date	Topic	Lab.
W	1/19/2022	Class introduction, syllabus, policies	Soil
F	1/21/2022	Invited speaker: Topic TBD	components
M	1/24/2022	Introduction: The geological cycle, soil origin	Grain size
W	1/26/2022	Introduction: Site investigation	dist.
F	1/28/2022	Index properties: Phase relationships	
M	1/31/2022	Index properties: Grain size distribution, Atterberg limits	Atterberg
W	2/2/2022	Index properties: Soil classification	limits
F	2/4/2022	Compaction	
M	2/7/2022	Quiz 1: Introduction, index properties, compaction, in-situ testing	Visual
W	2/9/2022	Water in soils: Groundawater table, pore pressure, total and effective stresses	classification
F	2/11/2022	Water in soils: Darcy's law	
M	2/14/2022	Water in soils: Permeability and hydraulic conductivity	Compaction
W	2/16/2022	Water in soils: One-dimensional seepage	
F	2/18/2022	Water in soils: 2D-3D seepage, flow nets, pore pressure, uplift force, seepage force	
M	2/21/2022	President's day: no class	In-situ
W	2/23/2022	Water in soils: piping	density
F	2/24/2022	Quiz 2: Water in soils	
M	2/28/2022	Induced stress: Approximations, Bousinesq's elastic solution	Permeability
W	3/2/2022	Induced stress: Bousinesq's elastic solution, superposition	
F	3/4/2022	Induced stress: Stress tensor, elastic deformations	
M	3/7/2022	Consolidation: Oedometer test, primary and secondary consolidation	Site
W	3/9/2022	Consolidation: Preconsolidation pressure, OCR	investigation
F	3/11/2022	Consolidation: Primary consolidation parameters	
M	3/14/2022	Spring break: no class	
W	3/16/2022	Spring break: no class	
F	3/18/2022	Spring break: no class	
M	3/21/2022	Consolidation: rate of consolidation	Bonus
W	3/23/2022	Consolidation: preloading, radial consolidation	
F	3/25/2022	Quiz 3: Induced stress and consolidaiton	
M	3/28/2022	State of stress: 2D stresses and Mohr's circle	Consolidation
W	3/30/2022	State of stress: principal stresses, stress invariants, rotations	
F	4/1/2022	State of stress:: Usage of Mohr's circle	
M	4/4/2022	State of stress: stress paths, simple shear, triaxial compression	Settlement
W	4/6/2022	Quiz 4: State of stress	estimates
F	4/8/2022	Shear strength: Mohr-Coulomb failure criteria	
M	4/11/2022	Shear strength: drained and undrained behavior	Unconfined
W	4/13/2022	Shear strength: Shear strength of clays	compression
F	4/15/2022	Shear strength: Shear strength of sands	test
M	4/18/2022	Quiz 5: Shear strength	Direct
W	4/20/2022	Lateral earth pressure: at-rest, passive, and active conditions [2]	shear
F	4/22/2022	Intro to slope stability [2]	
M	4/25/2022	Intro to bearing capacity [2]	Direct
W	4/27/2022	Maine's day: no class	shear
F	4/29/2022	Classes end: Q&A session	
M	5/2/2022	Final exam (1:30 PM- 3:30 PM) Williams Hall 110	

M: Monday - W: Wednesday - F: Friday

[2] This items may or may not be covered. It will be determined by how far the course has progressed.

RECAP

- We learned how to compute the increment of vertical stress for an infinitely loaded area.
- We learned about the Boussinesq equations and the distribution of stresses in an elastic semi-infinite medium.
- We described a numerical method for complex shapes and load distributions (more in CIE 460).
- Today we will learn about consolidation settlements.

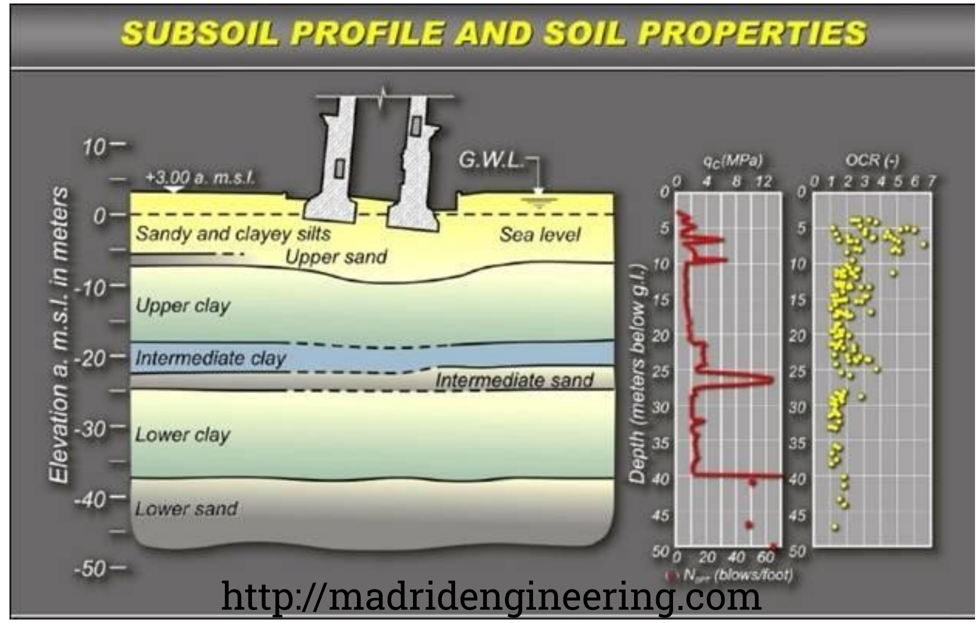
CONTENTS

- Case study
- Consolidation of soils
- Primary consolidation
- Consolidation curve
- Overconsolidation ratio
- Settlement due to primary consolidation

More in chapter 9 of Holtz et al. (2013)

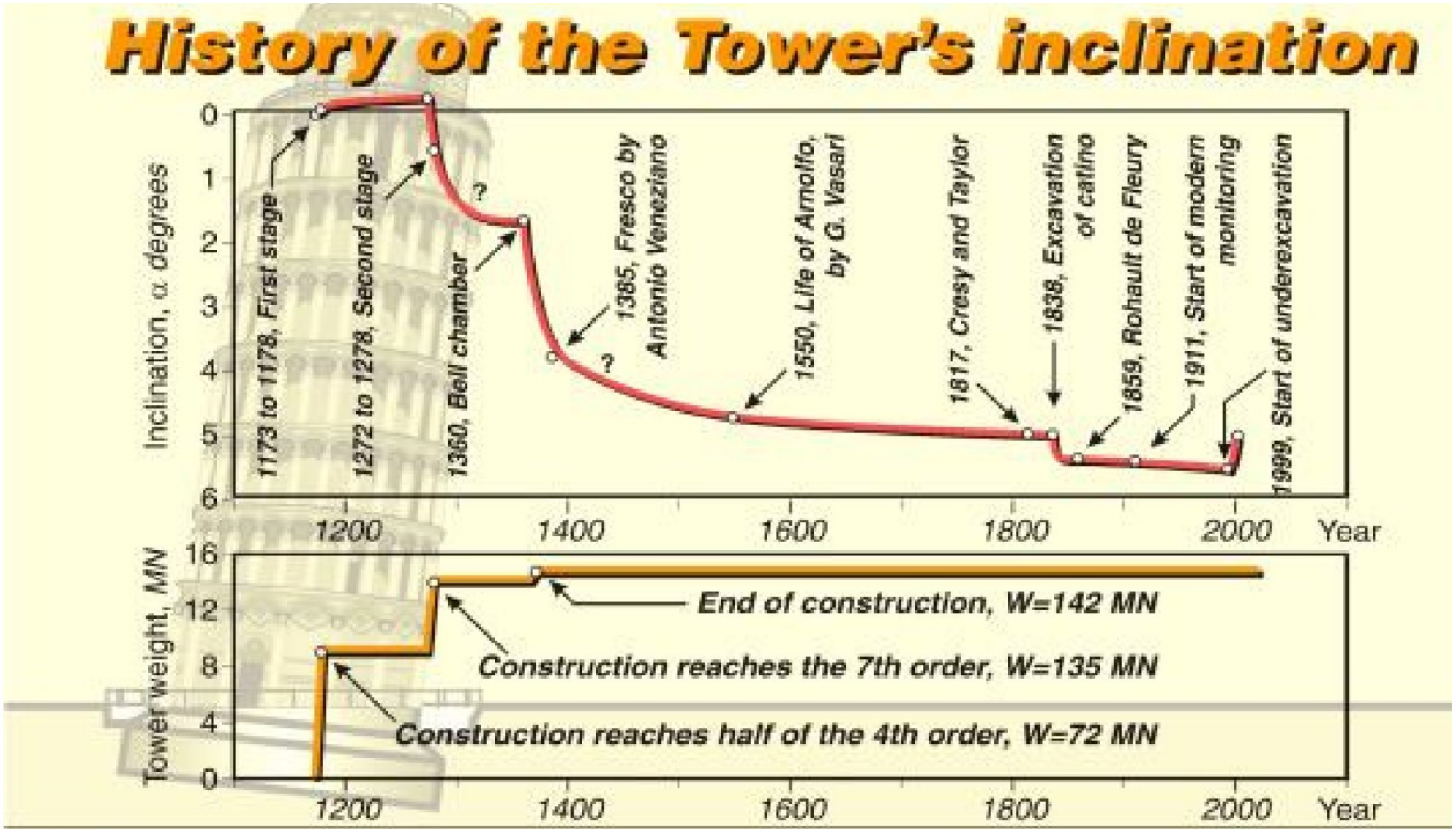
CASE HISTORY- LEANING TOWER OF PISA

Leaning is due to uneven settlements



http://madridengineering.com

CASE HISTORY- LEANING TOWER OF PISA

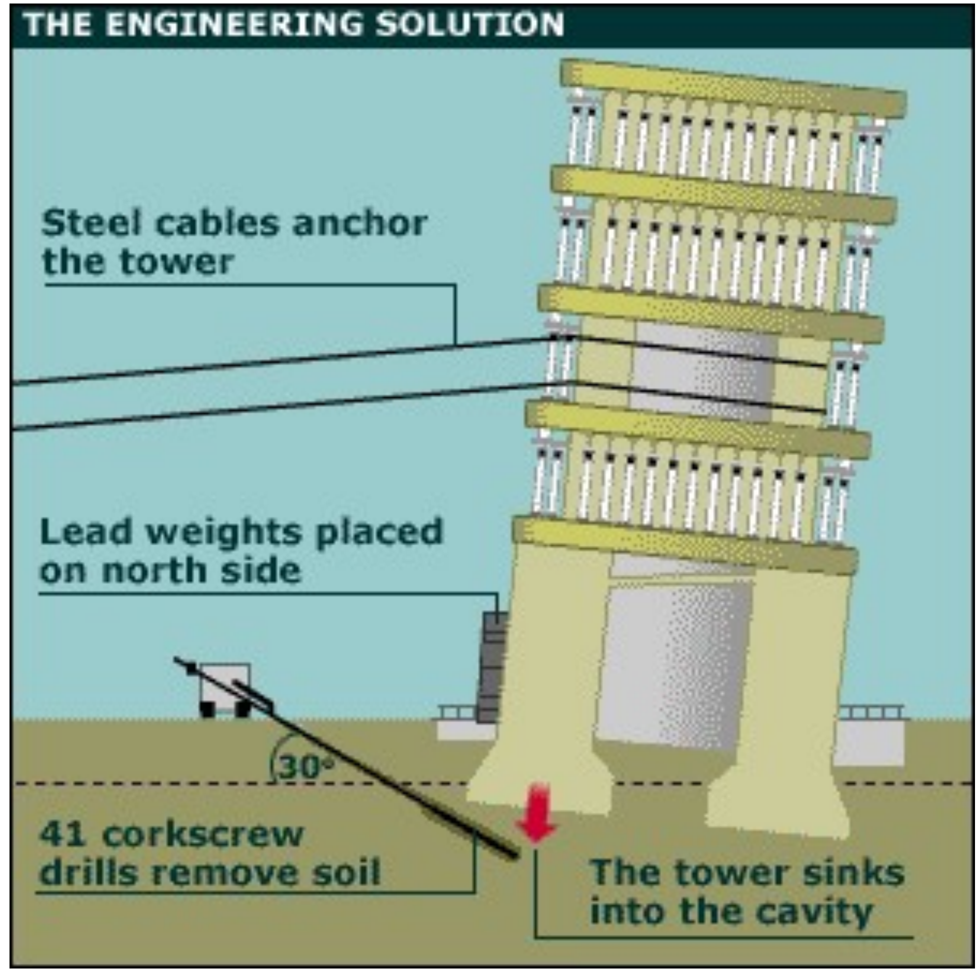


≡

CASE HISTORY- LEANING TOWER OF PISA

Remediation:

- Put heavy load on north side to compensate settlement on the south.
- Soil extraction mass (38 m^3) under the north side using angled holes.

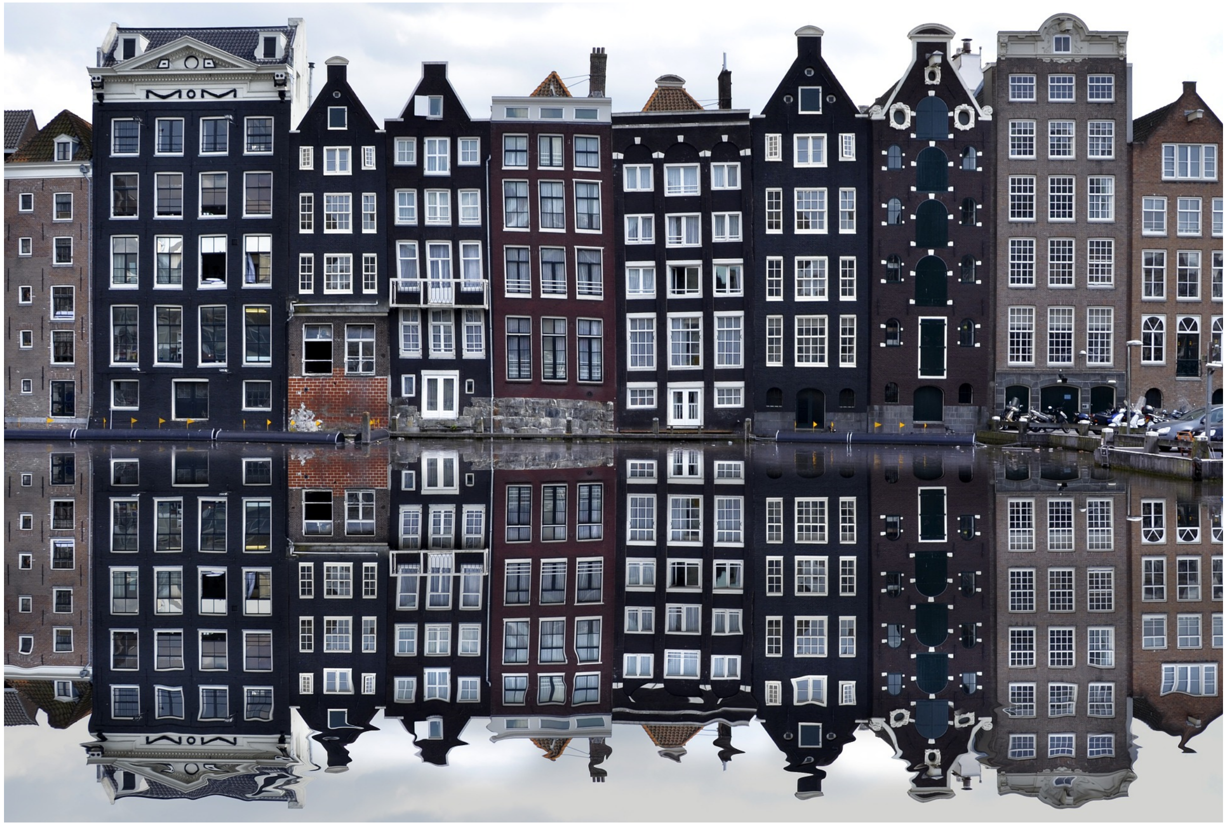


≡

OTHER SINKING PROBLEMS

Mexico City

OTHER SINKING PROBLEMS


Amsterdam

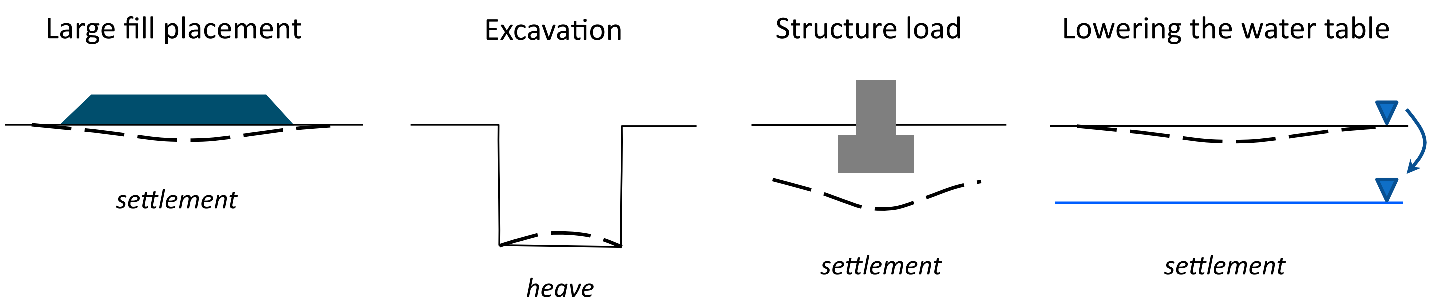
DEFORMATION OF SOILS

Recall: Terzaghi's principle $\longrightarrow$ Whenever there is change in effective stress there is a corresponding deformaiton.

$$\sigma' = \sigma - u$$

Examples:

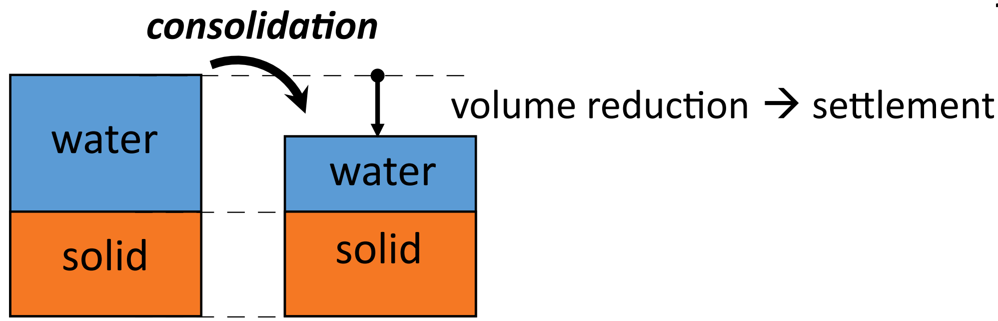
- Large fill placement $\longrightarrow \sigma \uparrow \longrightarrow \sigma' \uparrow \longrightarrow$ settlement
- Excavation $\longrightarrow \sigma \downarrow \longrightarrow \sigma' \downarrow \longrightarrow$ heave
- Structure load $\longrightarrow \sigma \uparrow \longrightarrow \sigma' \uparrow \longrightarrow$ settlement
- Lowering the water table $\longrightarrow u \downarrow \longrightarrow \sigma' \uparrow \longrightarrow$ settlement



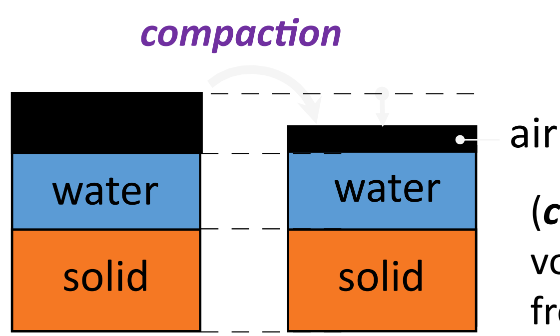
CONSOLIDATION

Def. CONSOLIDATION of soils (always in satudated soils!)

Process by which soil volume decreases due to water scaping from the soil.

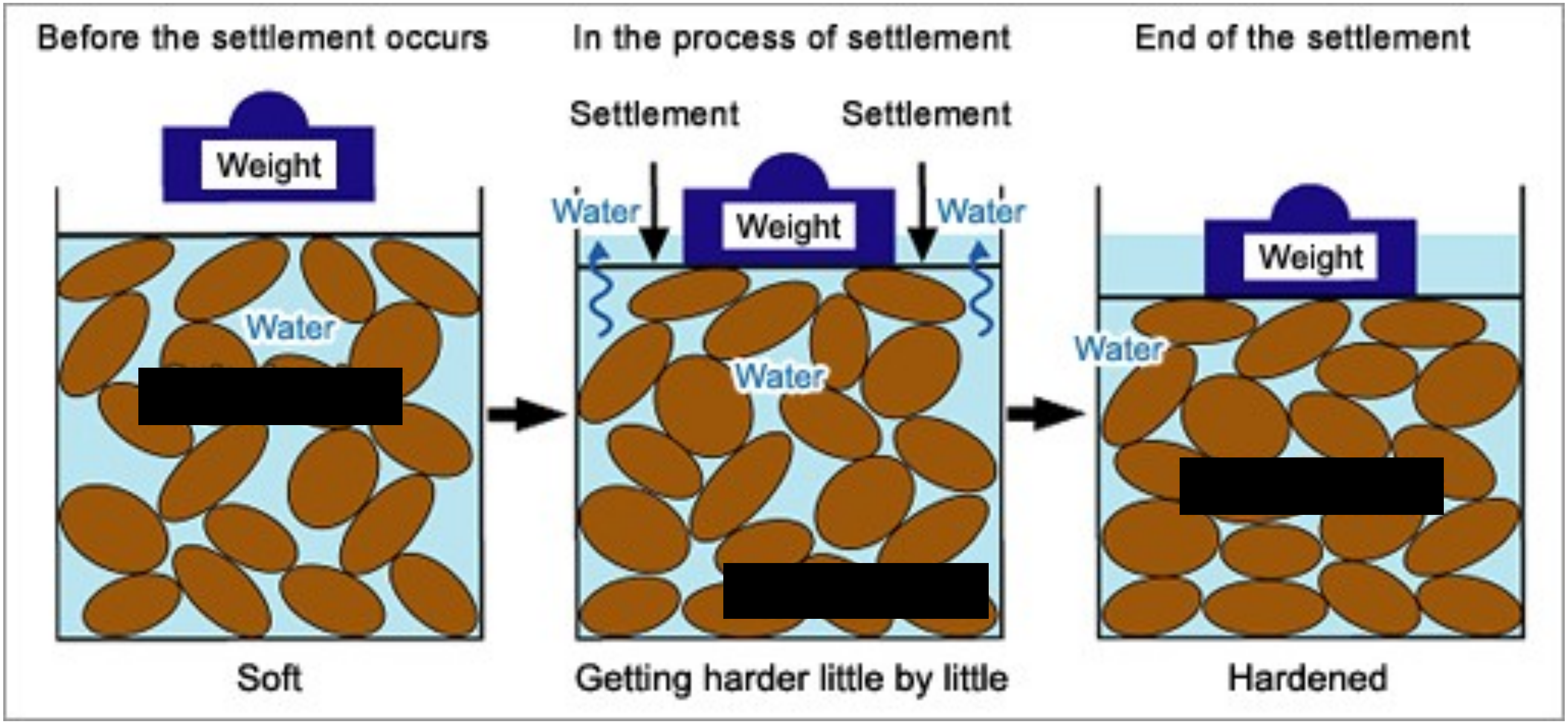


Important!! Do not confuseconsolidation with *compaction*



(***compaction***: reduction of soil volume due to air escaping from the soil)

CONSOLIDATION



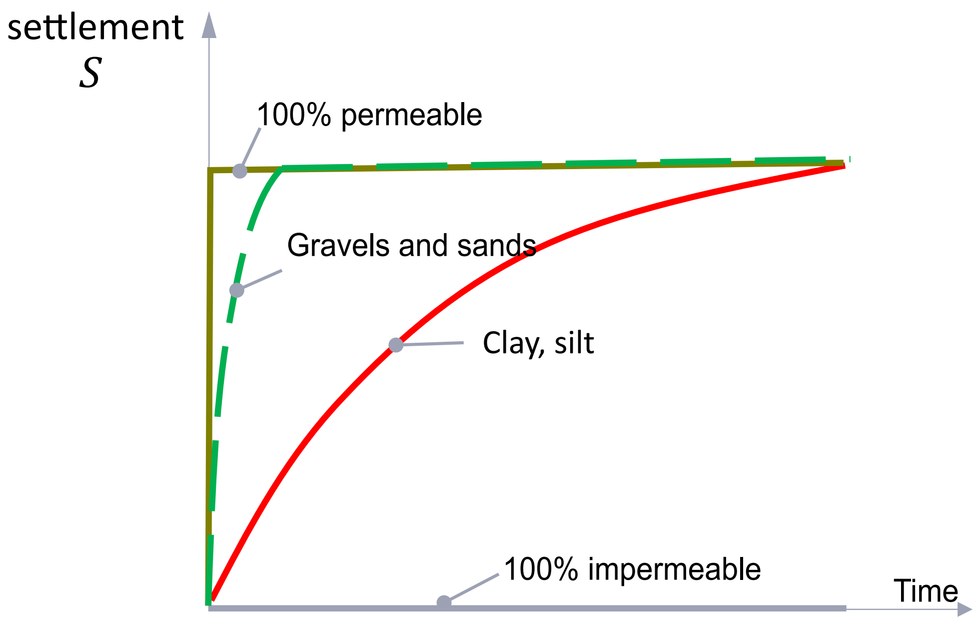
EFFECT OF DRAINAGE

If we apply a load on...

- 100% impermeable soil : water cannot leave $\longrightarrow$ no consolidation $\longrightarrow$ no settlement.
- 100% permeable soil : Water can leave instantaneously $\longrightarrow$ instantaneous consolidation $\longrightarrow$ instantaneous settlement.
- Gravel and sands (very permeable): Water can leave rapidly $\longrightarrow$ rapid consolidation $\longrightarrow$ rapid settlement.
- Clay, silty soils (close to impermeable): Water leaves the soil very slowly $\longrightarrow$ slow consolidation $\longrightarrow$ delayed settlement

≡

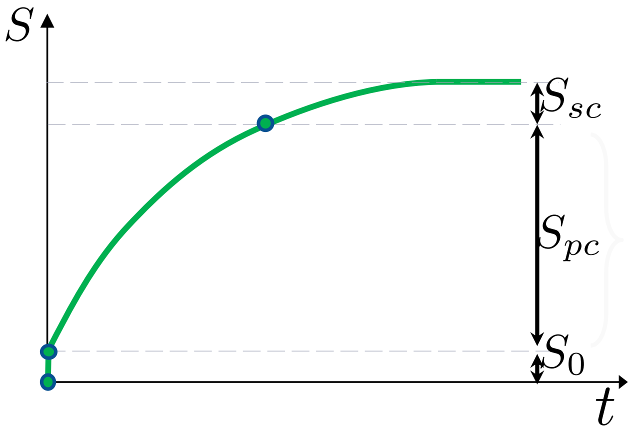
EFFECT OF DRAINAGE

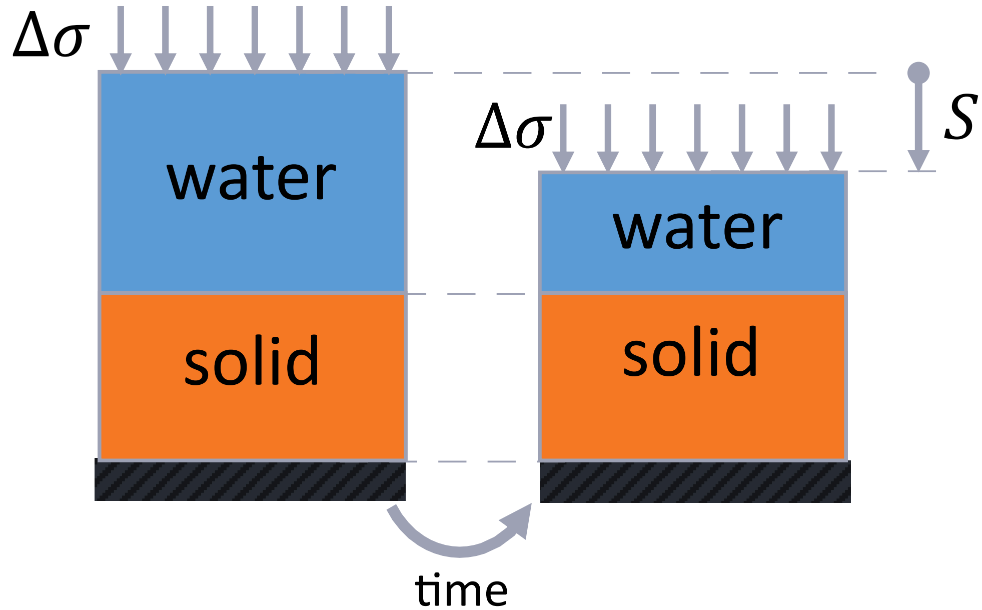


In practice, consolidation in clays and silts is the most problematic because it occurs well after the project has finished. In this module, we will study the consolidation of fine soils.

PRIMARY CONSOLIDATION

The settlement due to consolidation in clays can be divided in three different parts:

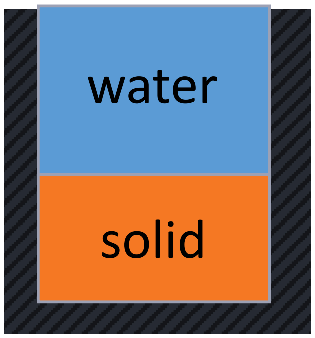




- S_0 = Instantaneous settlement
- S_{pc} = Primary consolidation
- S_{sc} = Secondary consolidation

PRIMARY CONSOLIDATION PROCESS

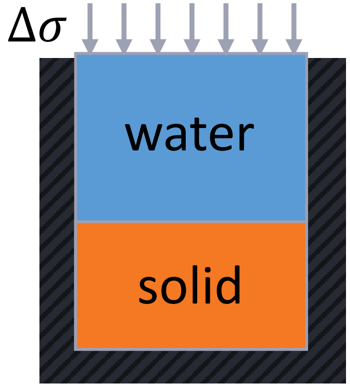
$t < t_0$ Initial conditions



$$\sigma = \sigma_0$$
$$u = u_0$$
$$\sigma' = \sigma'_0$$

Initial conditions due to geostatic loading, hydrostatic conditions

t_0 Apply external load



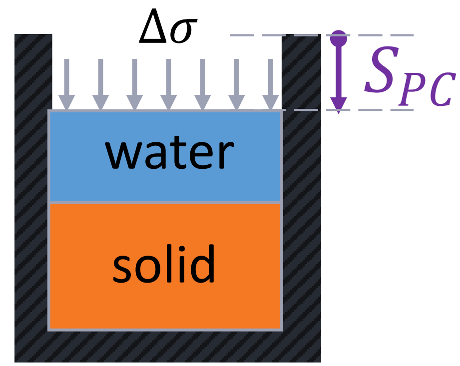
$$\sigma = \sigma_0 + \Delta\sigma$$
$$u = u_0 + \Delta\sigma$$
$$\sigma' = \sigma'_0$$

The external load is initially fully supported by the water

<u>Effective stress increases</u> at the same rate that pore water pressure dissipates.

→ <u>Vertical settlement</u>

t_f End of primary consolidation

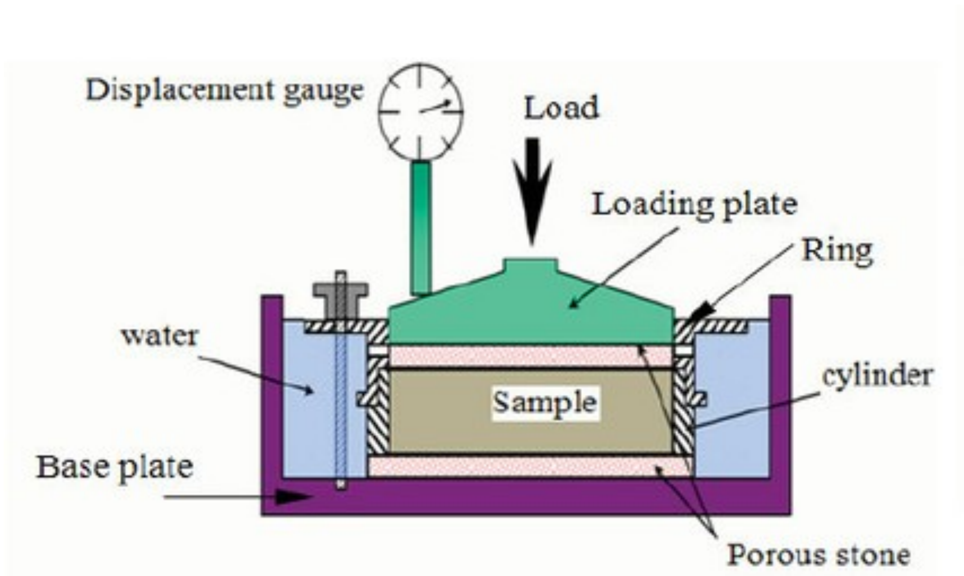


$$\sigma = \sigma_0 + \Delta\sigma$$
$$u = u_0$$
$$\sigma' = \sigma'_0 + \Delta\sigma$$

Finally, pore water pressure returns to the hydrostatic and the external load is fully supported by the solid skeleton → $\Delta\sigma' = \Delta\sigma$

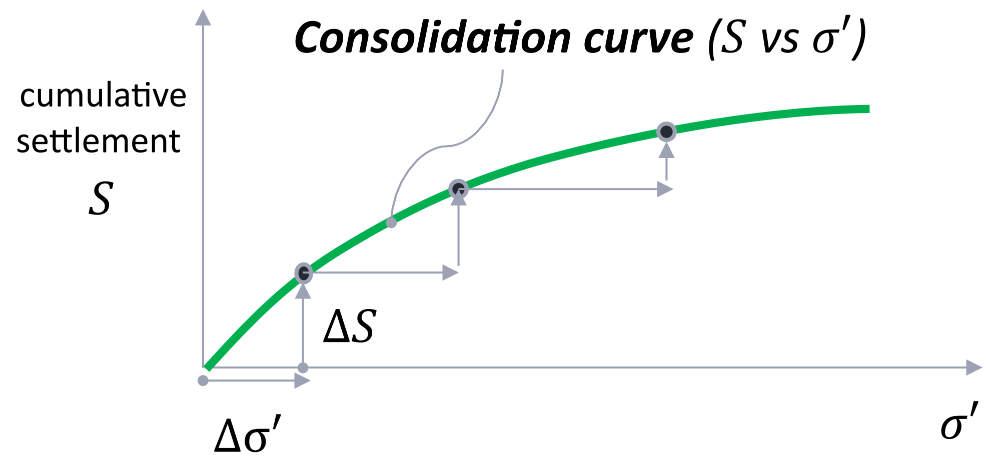
OEDOMETER/CONSOLIDATION TEST

Laboratory test to determine soil's consolidation properties



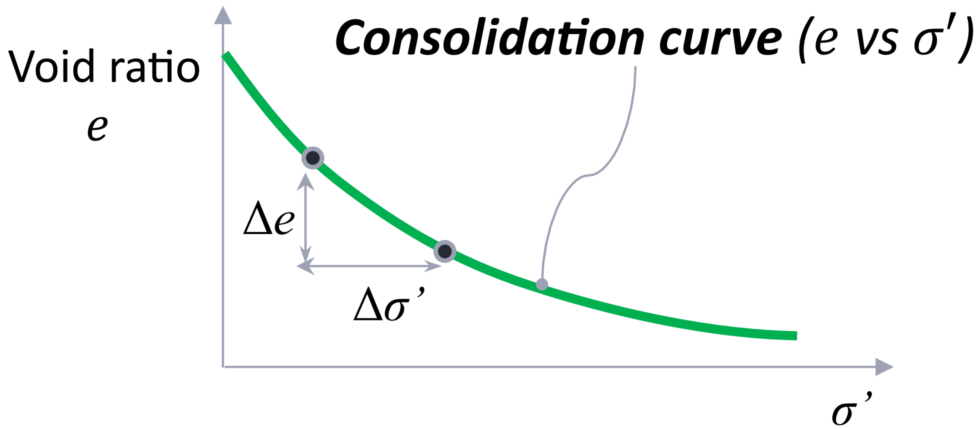
Iterative process:

1. Increase vertical load $\Delta\sigma$
2. Wait until pore pressure is 100% dissipated (about 24 h).
3. Measure the settlement ΔS
4. Plot cummulative stress vs settlement.



≡

SETTLEMENT VS. VOID RATIO

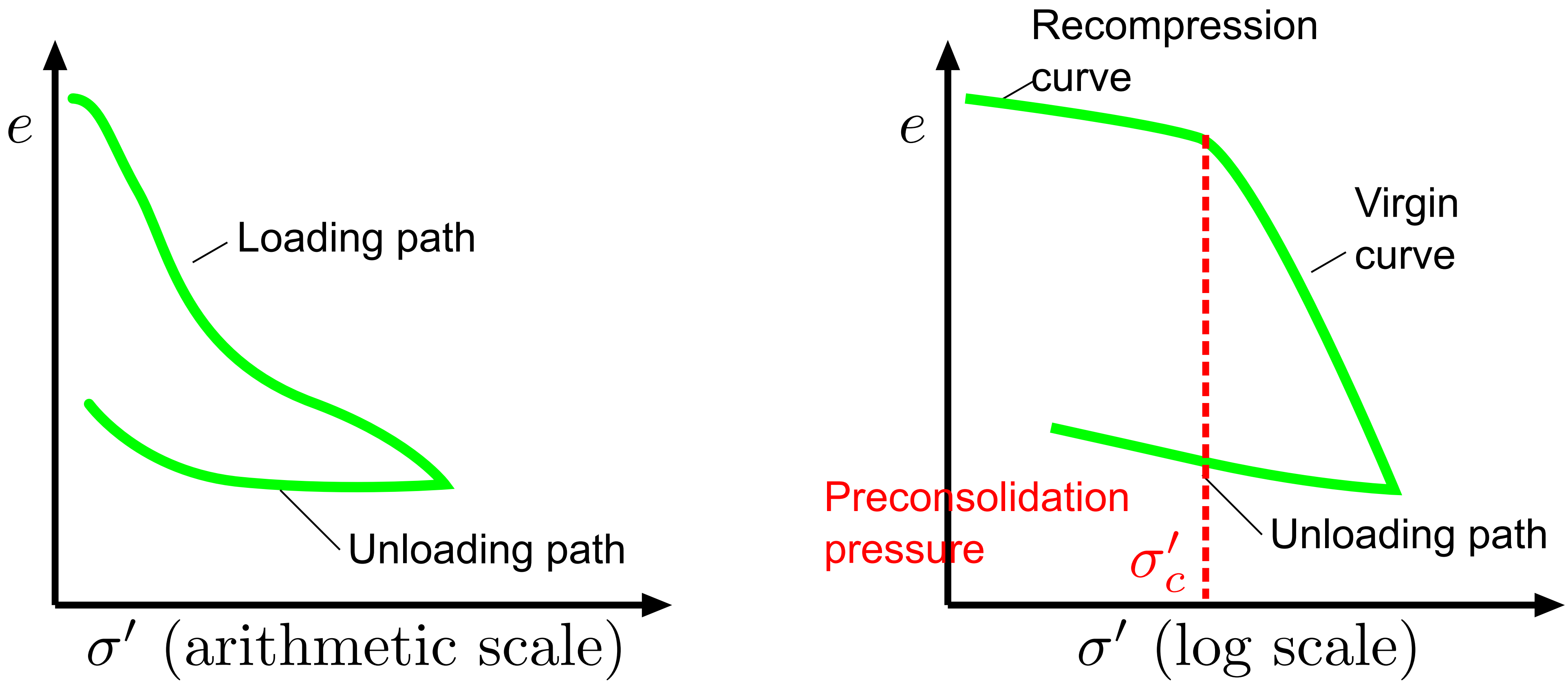


$$\Delta e = \frac{\Delta H}{H_0}(1 + e_0)$$

- H_0 = initial height of specimen
- ΔH = settlement (S)
- e_0 = void ratio
- Δe = change of void ratio

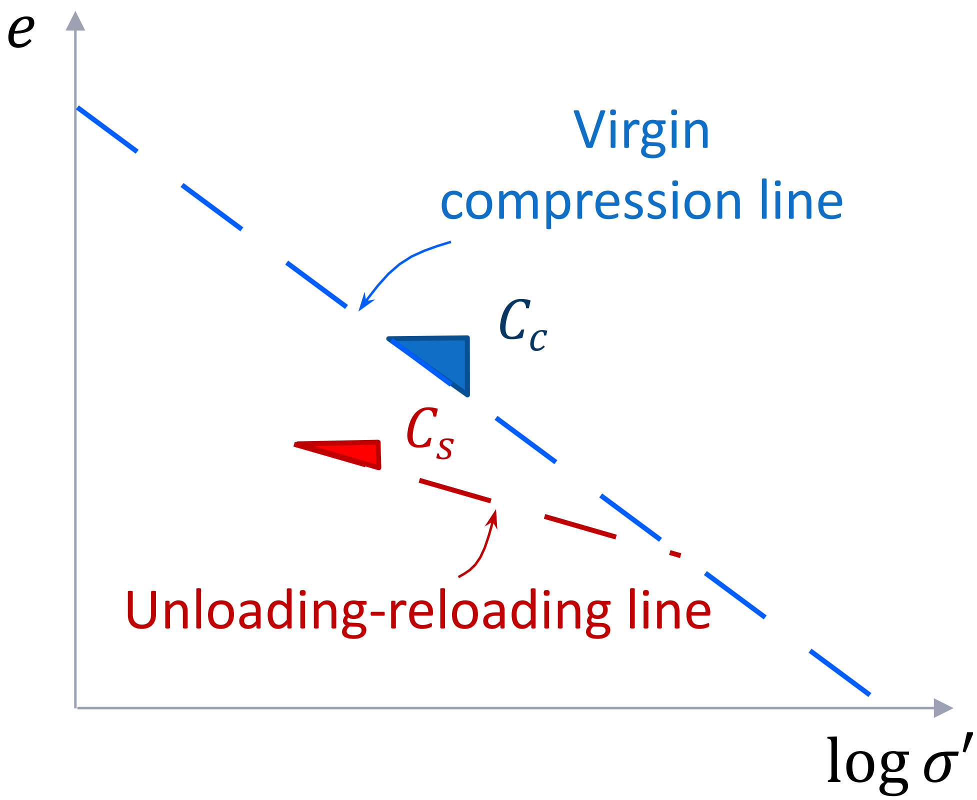
It is more convenient to plot the consolidation curve in terms of void ration e than settlement S

THE CONSOLIDATION CURVE



≡

CONSOLIDATION PARAMETERS



Virgin compression line

$$\Delta e = -C_c \Delta \log(\sigma')$$

$$C_c = \text{compressive index}$$

Unloading-reloading line

$$\Delta e = -C_s \Delta \log(\sigma')$$

$$C_r = \text{swelling index}$$

≡

CONSOLIDATION PARAMETERS

Typical values of C_c and C_r

- $C_c < 0.05$ "low" compressibility
- $0.05 < C_c < 0.25$ "medium" compressibility
- $C_c > 0.25$ "high" compressibility

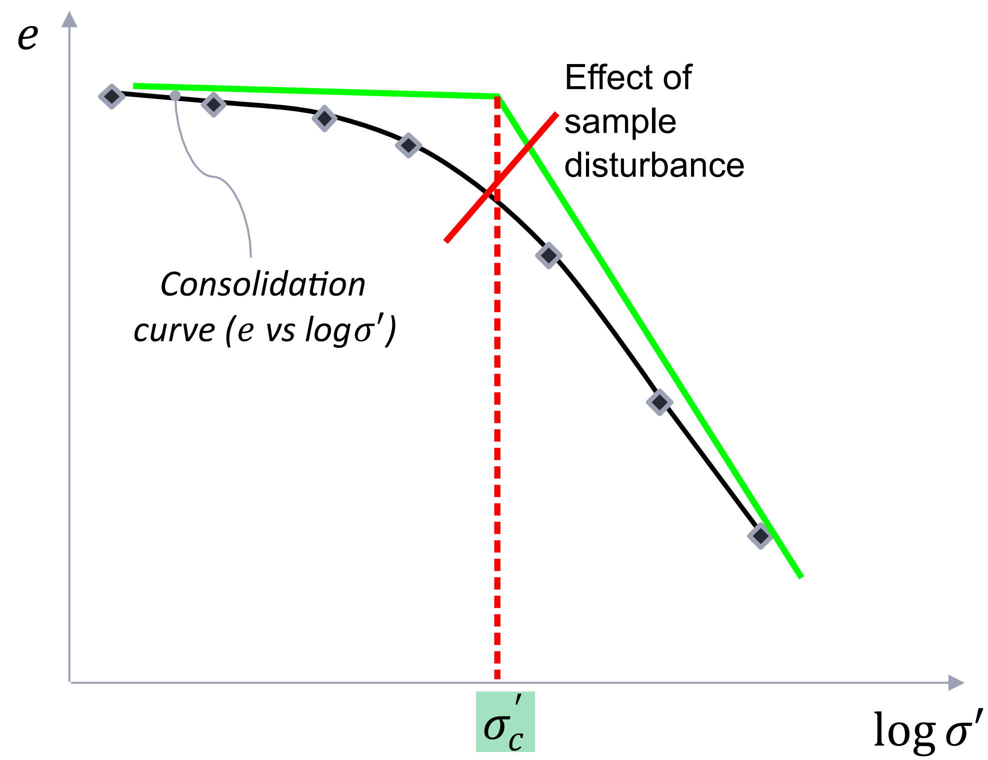
$$C_S \approx 1/5 - -1/10C_c$$

Correlation proposed by Terzaghi and Peck (1967) for undisturbed clays of low to medium plasticity.

$$C_c = 0.009(LL - 10)$$

≡

EFFECT OF SAMPLE DISTURBANCE



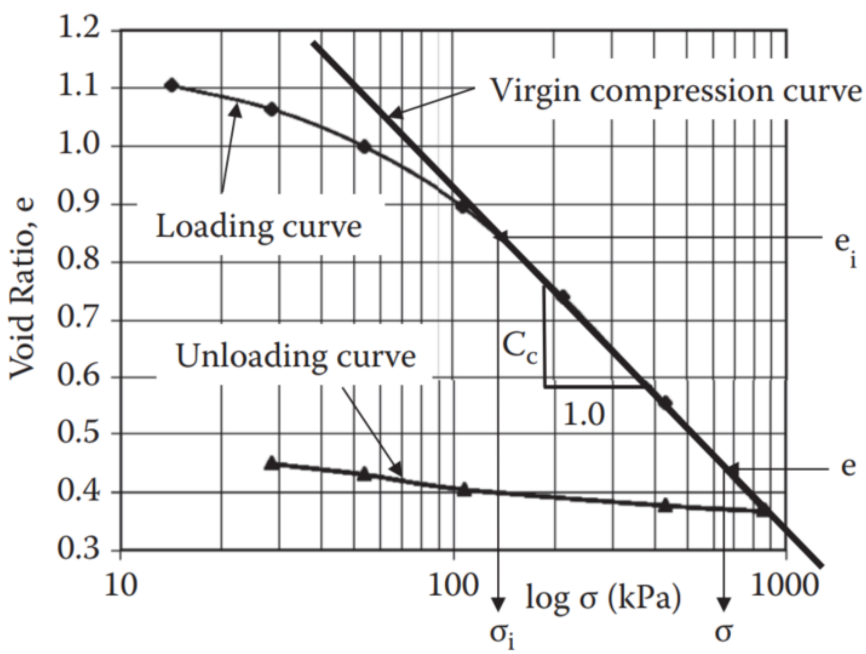
We use Casagrande's procedure to correct for disturbance:

1. Plot consolidation curve form experimental data.
2. Choose point of maximum curvature.
3. Draw horizontal line through such point
4. Bisect the angle between the lines in steps 3 and 4.
5. Draw virgin compression line.
6. Intersection of lines in step 5 and 6 is σ'_c

≡

EXAMPLE 5.1

Find C_c, C_r, and σ'_c for the consolidation test results shown in the figure below



From Ishibashi and Hazarika (2010)

OVERCONSOLIDATION RATIO (OCR)

Ratio between the preconsolidation stress σ'_c and the in-situ effective stress σ'_0

$$OCR = \frac{\sigma'_c}{\sigma'_0}$$

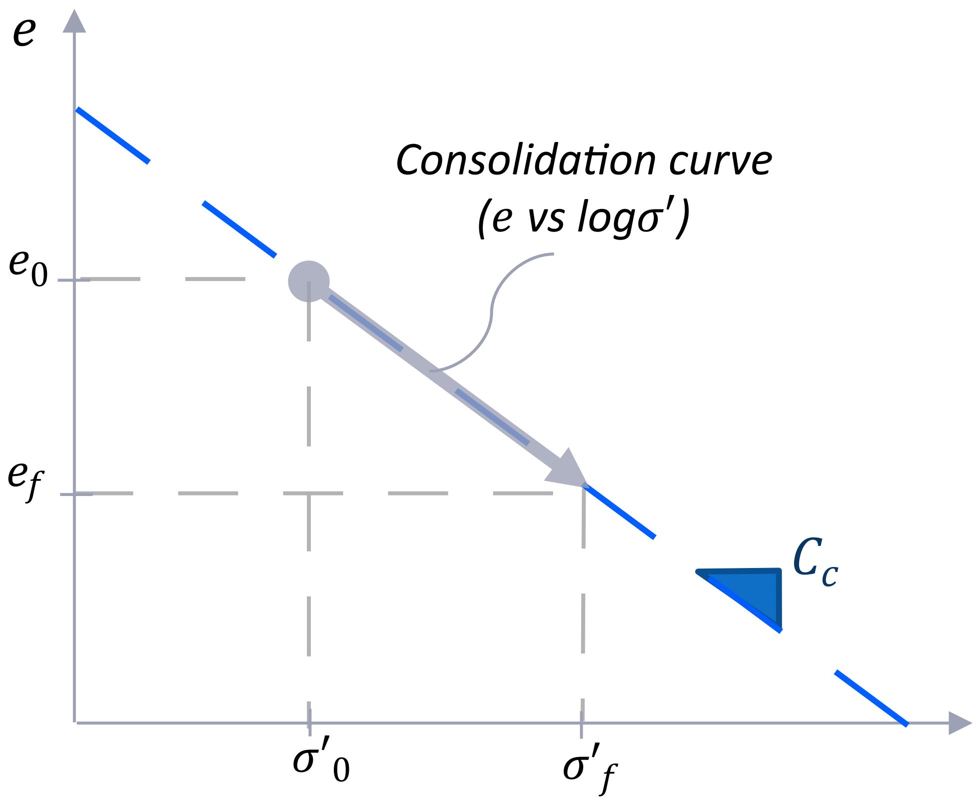
- Normally consolidated soil: $OCR = 1 \longrightarrow \sigma' c = \sigma'_0$
- Overconsolidated soil: $OCR > 1 \longrightarrow \sigma'_c > \sigma'_0$

≡

- Soils (clay) is a history dependent material $\longrightarrow$ "have memory"
- The OCR give us information about the loading geological history of soil
- Similarly, if we know some details about the geological history we can make sense of OCR values

PRIMARY CONSOLIDATION SETTLEMENT

Settlement in normally consolidated soils

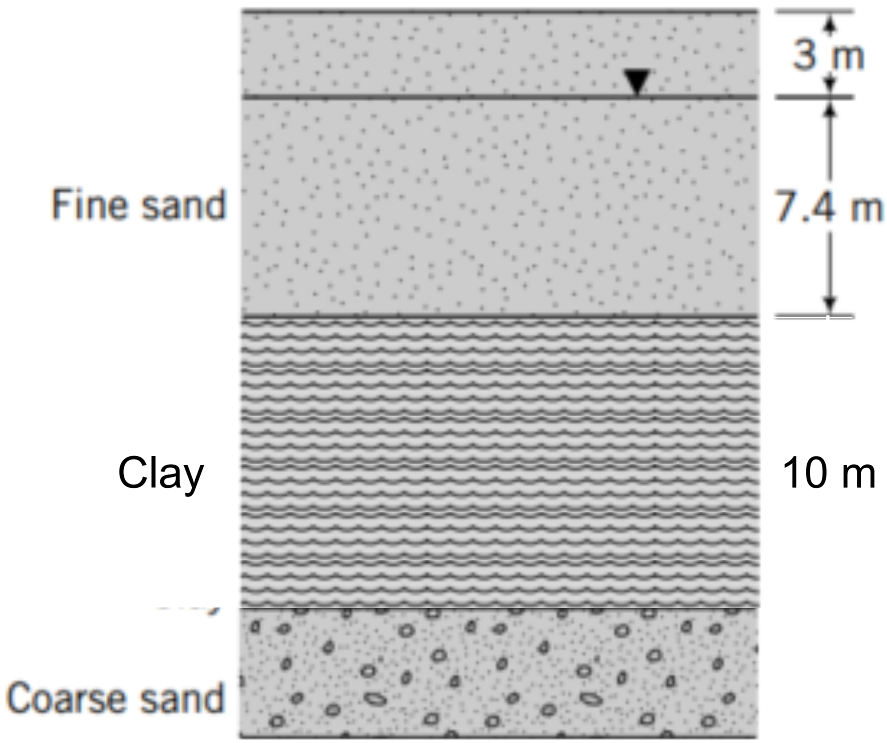


- Stress path moves along virgin curve
- Then:

$$\Delta H = C_c \frac{H_0}{1+e_0} \log\left(\frac{\sigma'_f}{\sigma'_0}\right)$$

≡

EXAMPLE 5.2



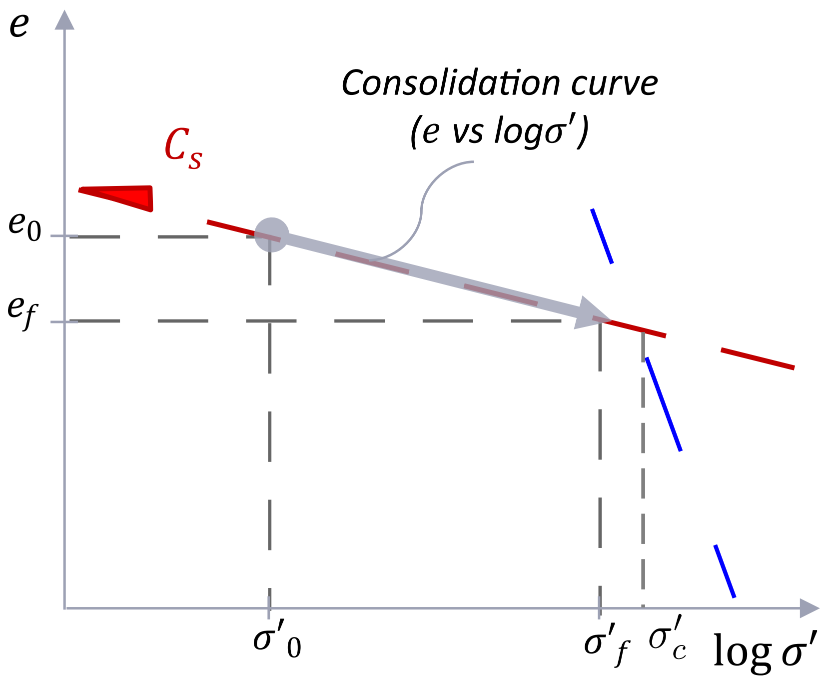
The soil profile at a site for a proposed office building consists of a layer of fine sand 10.4 m thick above a layer of soft, normally consolidated clay 10 m thick. Below the soft clay is a deposit of coarse sand. The groundawater table was observed at 3 m below ground level. The void ratio of the sand is 0.76 and the water content of the clay is 43%. The building will impose a vertical stress increase of 200 kPa at the middle of the clay layer. Estimate the primary consolidation settlement of the clay. Assume the soil above the water table to be saturated, $C_c = 0.3$, and $G_s = 2.7$.

≡

PRIMARY CONSOLIDATION SETTLEMENT

Settlement in overconsolidated soils. Case a:

$$\sigma'_f < \sigma'c$$



- Stress path moves along recompression curve
- Then:

$$\Delta H = C_r \frac{H_0}{1 + e_0} \log \left(\frac{\sigma'_f}{\sigma'_0} \right)$$

≡

EXAMPLE 5.3

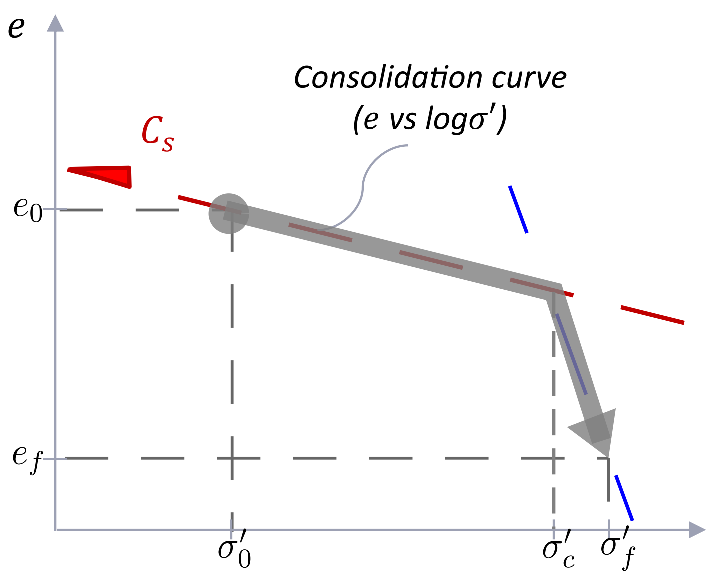
Solve problem 5.2 but assuming $OCR = 4$, $w = 38\%$, and $C_r = 0.05$. All other soil values given in Example 5.2 remain unchanged. Determine the appropriate euqtion to use. Note that the unit weight of sand is unchanged, only the clay unit weight is changed.

≡

PRIMARY CONSOLIDATION SETTLEMENT

Settlement in overconsolidated soils. Case b:

$$\sigma'_f > \sigma'c$$



- Stress path moves along recompression curve and virgin curve
- Then:

$$\Delta H = C_r \frac{H_0}{1+e_0} \log(OCR) + C_c \frac{H_0}{1+e_0} \log\left(\frac{\sigma'_f}{\sigma'_c}\right)$$

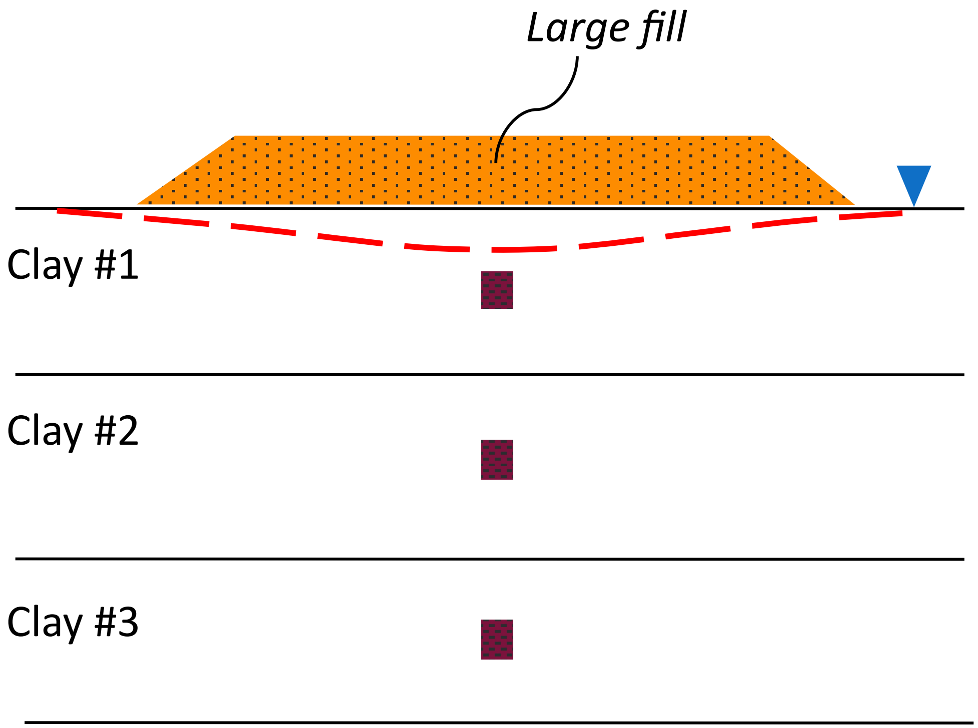
≡

EXAMPLE 5.4

Solve problem 5.3 assuming $OCR = 1.2$. Determine the primary consolidation settlement.

≡

PRIMARY CONSOLIDATION IN LAYERED SOILS



1. Determine initial vertical effective stresses (σ_0') at the center of soil layers of concern. If thick layers, divide and find σ_0' for centers of sub-layers.
2. Extract soil sample at the center of each layer or sub-layer and run consolidation tests.
3. Determine preconsolidation stress σ_c' and initial void ratio $e_0 = G_s w_0$ for layers of concern.
4. Determine C_c and C_r for layers of concern.
5. Determine $\Delta\sigma$ due to external load at the center of each layer of concern.
6. Compute settlement ΔH for each individual layer of concern considering initial high of each layer H_0.
7. Total settlement $= \sum \Delta H$

EXAMPLE 5.5

Solve problem 5.2 subdividing the clay layer into 3 sublayers. How does the result compares with solution of problem 5.2?