SETTLEMENTS OF FOUNDATIONS

There are 3 main types of settlements in soils:

Short-term i. <u>Immediate Settlement:</u> (S_i) : This is due to elastic deformation which occurs immediately on loading with no change in moisture content.

Long-term
ii. Primary <u>Consolidation Settlement :</u> (S_c): This is due to the squeezing out of the pore fluid, Time dependent.

iii. <u>Secondary Consolidation settlement</u> : (S_s): Due to structural change (e.i. particle reorientation)

$$\Sigma S = \underbrace{S_i}_{\text{cohesionless soils}} + \overbrace{S_c + S_s}^{\text{cohesive soils}}$$

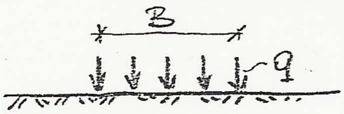
S_s → Only in sensitive, organic clays.

S_i:
* Not time depend.
* small fraction of total settl. in saturated clays.
* Elastic theory is used.

S_c:
* Consolidation theory is valid.
* Time dependent
* Large fraction of total settl. in clay soils.
* None in cohesionless soils.

I. Immediate Settlement. (S_i)

a) For semi-Infinite, homogeneous, isotropic foundation



$$S_i = \frac{qB}{E}(1-\mu^2)\, I_s$$

NOTE: $D_f = 0$

Compressible layer $\to \infty$

q = Intensity of uniform Loading for flexible footing (net found. pressure)

E = Young's modulus (Elastic Modulus)

μ = Poissons ratio $\left(\frac{\varepsilon_h}{\varepsilon_v}\right)$ $\frac{\text{Lateral Strain}}{\text{Vertical Strain}}$

$\mu = 0.5$ for saturated clays

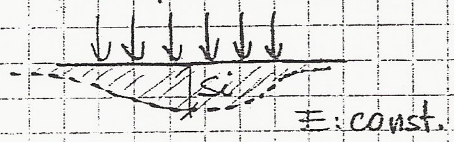
0.25 - 0.35 for sands.

B = Width of rectangular area or diameter of circular area

I_s = Influence factor : depends on rigidity & shape of the footing. Table 3.1

Note: Stress distribution beneath footings.

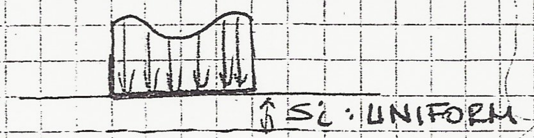
FLEXIBLE FTG
Displacements



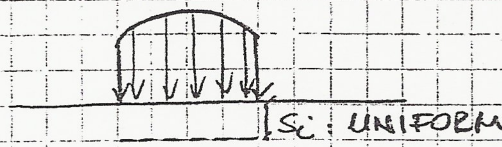
CLAY

SAND

RIGID FTG:
Contact Pressures



CLAY



SAND

I_s : Flexible Area:

Shape	I_s Center	I_s Corner	I_s Average
Square	1.12	0.56	0.95
Rect $L/B=2$	1.52	0.76	1.30
" $L/B=5$	2.10	1.05	1.83
Circle	1.0	0.64	0.85.

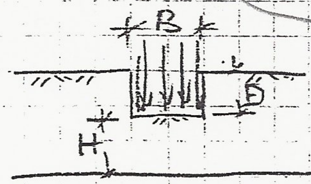
Table 3.1

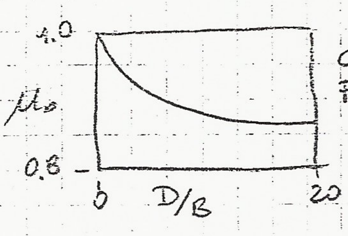
b) If: Limited thickness of Compressible Layer & $D_f \neq 0$: → CE 306 TUTORIAL 2 (problem 3)

~~Solutions are available~~

For example: Saturated Clay $\mu = 0.5$

$$S_i = \mu_0 \mu_1 \frac{qB}{E}$$





CRAIG Fig 5.15 P. 177

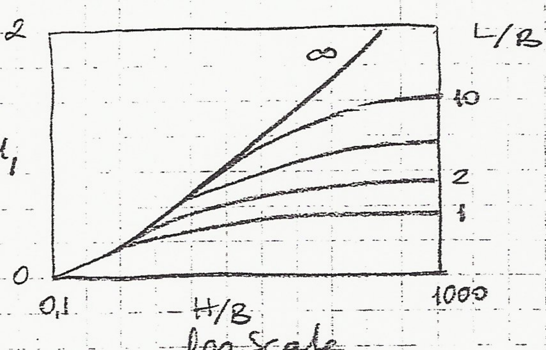
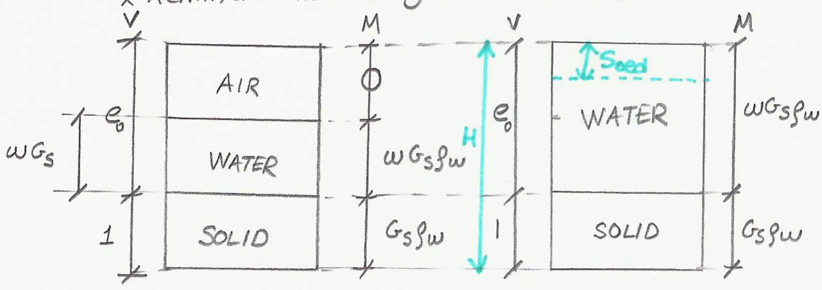


FIG 3.3

II. PRIMARY CONSOLIDATION SETTLEMENT (S_c)

* Remind: Phase Diagrams (CE 363)



-GENERAL- -SATURATED SOIL-

For 1-D consolidation settlement (S_{oed}):

$$\frac{S_{oed}}{H} = \frac{\Delta e}{1+e_0} \Rightarrow \boxed{S_{oed} = \frac{1}{1+e_0} \cdot \Delta e \cdot H}$$

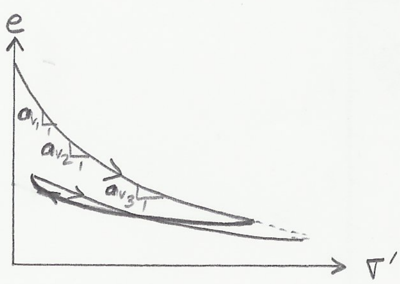
where; H: thickness of compressible soil layer

Δe: change in void ratio
(as consolidation proceeds, Δe increases)

e_0: initial void ratio
(at the beginning of consolidation)

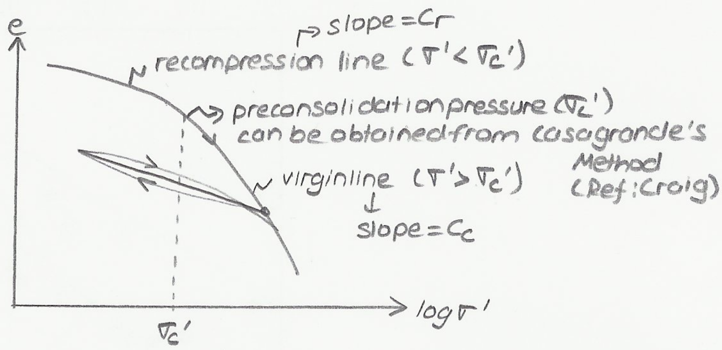
S_{oed}: oedometric settlement
(1-D cons. sett.)

* Remind: consolidation (oedometer) test (CE 363)



-e versus σ'-

-OR-



- e versus $\log\sigma'$ -

$$a_v = \frac{\Delta e}{\Delta\sigma'}$$

coefficient of volume compressibility

$$\boxed{m_v = \frac{1}{1+e_0} \cdot a_v = \frac{1}{1+e_0} \cdot \frac{\Delta e}{\Delta\sigma'}}$$

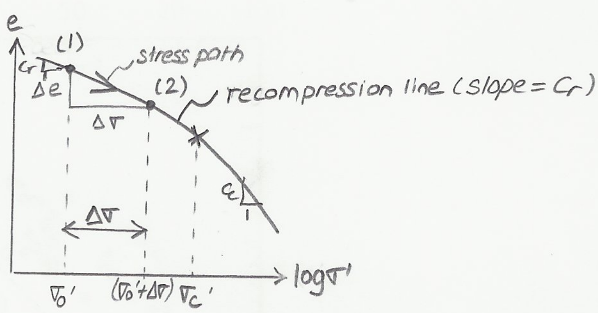
$$\boxed{S_{oed} = m_v \times \Delta\sigma' \times H}$$

* m_v is defined for different ranges of stress by discretizing the above e vs. σ' curve.

σ_0': initial effective overburden stress

$\Delta\sigma$: change in stress due to loading
(can be obtained from 2V:1H approximate method; Ref: CE 366)

(i) if $\sigma_0' < \sigma_c'$ and $\sigma_0' + \Delta\sigma < \sigma_c'$

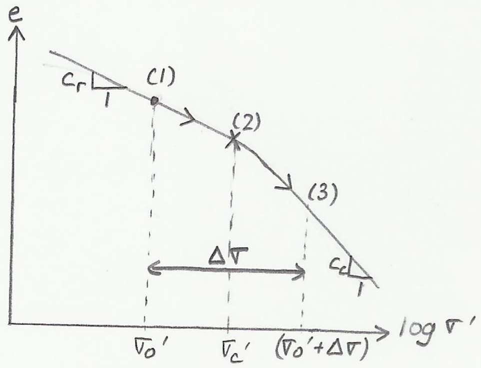


$$\Delta e = C_r[\log(\sigma_0' + \Delta\sigma) - \log(\sigma_0')] = C_r \log\left(\frac{\sigma_0' + \Delta\sigma}{\sigma_0'}\right)$$

$$\boxed{S_{oed} = \frac{C_r}{1+e_0} H \log\left(\frac{\sigma_0' + \Delta\sigma}{\sigma_0'}\right)}$$

where; C_r: recompression index

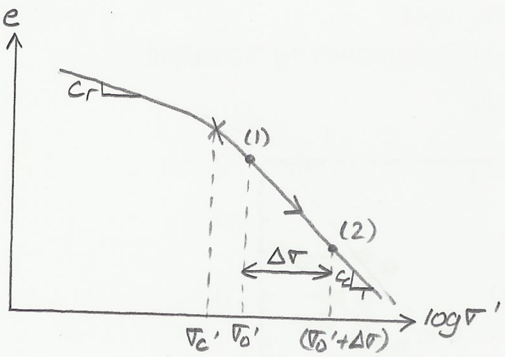
(ii) if $\sigma_0' < \sigma_c'$ and $\sigma_0' + \Delta\sigma > \sigma_c'$



$$\boxed{S_{oed} = \underbrace{\frac{C_r}{1+e_0} H \log\left(\frac{\sigma_c'}{\sigma_0'}\right)}_{(1)-(2)} + \underbrace{\frac{C_c}{1+e_0} H \log\left(\frac{\sigma_0' + \Delta\sigma}{\sigma_c'}\right)}_{(2)-(3)}}$$

where; C_c : compression index

(iii) if $\sigma_0' > \sigma_c'$



$$\boxed{S_{oed} = \frac{C_c}{1+e_0} H \log\left(\frac{\sigma_0' + \Delta\sigma}{\sigma_0'}\right)}$$

NOTES:

① if loading is on a very wide area then; $\boxed{S_c \cong S_{oed}}$

② if loading is on a foundation/footing (limited area) then; $\boxed{S_c = S_{oed} \times \mu_{SB}}$

where μ_{SB} : Skempton - Bjerrum correction factor (depends on H/B and pore pressure parameter "A") B: width of foundation

③ OCR: over consolidation ratio ⇒ $OCR = \dfrac{\text{Maximum effective pressure through stress history } (\sigma_c')}{\text{Present effective pressure } (\sigma_0')}$

if $OCR = 1.0$ → soil is normally consolidated (NC) → $\sigma_0' = \sigma_c'$

if $OCR > 1.0$ → soil is overconsolidated (OC) → $\sigma_c' = OCR \times \sigma_0'$

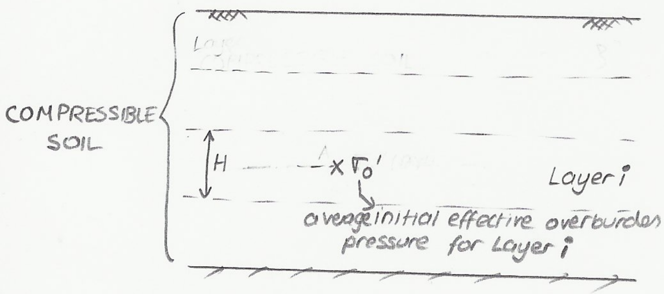
④ You should calculate $\Delta\sigma$ by using q_{net}. So you have to know how to calculate q_{net}.
(Refer to CE 366)

⑤ For rectangular area $\Delta\sigma = \dfrac{q_{net} \times L \times B}{(L+z)(B+z)}$, Remind for others? (ex: circular, strip ?)

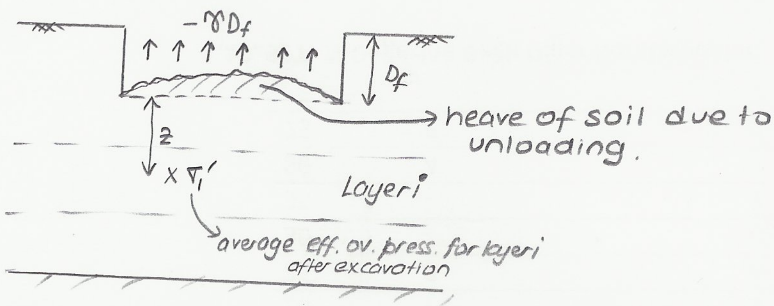
⑥ SETTLEMENT CALCULATIONS ARE ALWAYS DONE FOR LAYERS UNDER THE FOUNDATION!

⊛ STAGES OF CONSTRUCTION:

(i) INITIALLY:

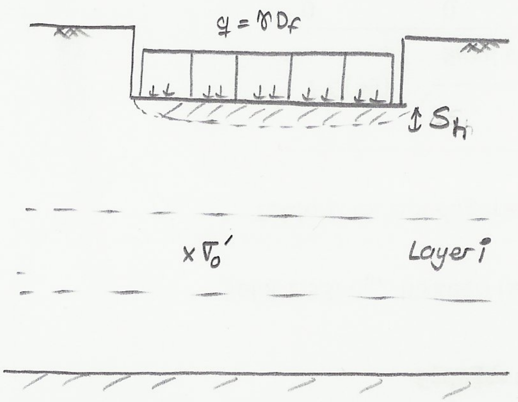


(ii) EXCAVATION DOWN TO D_f: (path 1)

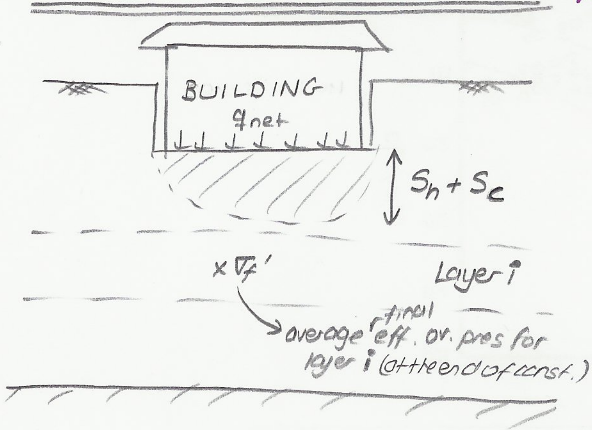


(iii) CONSTRUCTION UP TO $q = \gamma D_f$ amount of load:

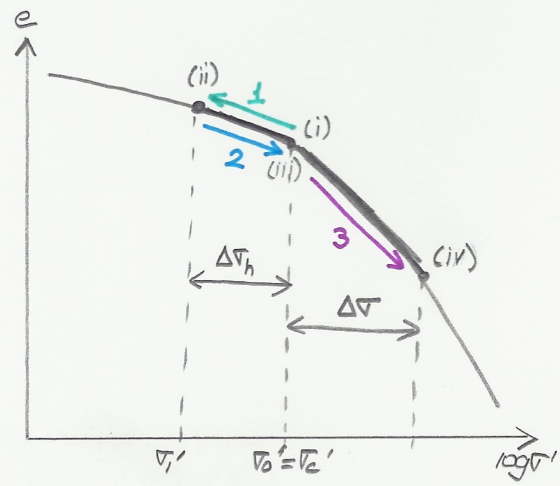
(path 2)



(iv) AT THE END OF CONSTRUCTION: (path 3)



Say soil is NC:



where; $\Delta\sigma_h$: decrease in stress due to unloading (excavation) causing heave of soil.

For rectangular area (L×B)

$$\boxed{\Delta\sigma_h = \frac{(\gamma D_f) \times L \times B}{(L+z)(B+z)}}$$

As a result;

$$\boxed{S_T = S_i + (S_h + S_c)}$$

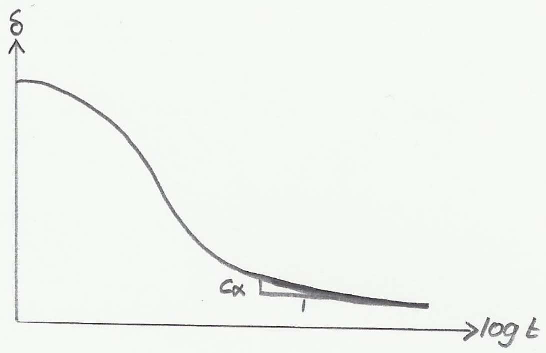
where;

$$\boxed{S_h = \frac{C_r}{1+e_0} H \log\left(\frac{\sigma_0' + \Delta\sigma_h}{\sigma_0'}\right)}$$

settlement due to heave.

S_h : this is an additional settlement you should add to primary consolidation settlement.

III. SECONDARY CONSOLIDATION (CREEP) SETTLEMENT:



$$\boxed{S_s = \frac{C_\alpha}{1+e_0} H \log \frac{t}{t_p}}$$

where; t_p : time corresponding to primary consolidation

t : time period for which the settlements are computed.

★ Usually $t/t_p < 10$ for field cases.

For inorganic clays and silts $C_\alpha / C_c = 0.04 \mp 0.01$

For organic clays and silts $C_\alpha / C_c = 0.05 \mp 0.01$

For peats $C_\alpha / C_c = 0.06 \mp 0.06$