Soil Settlement

By

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Soil Settlement

Total Soil Settlement = Elastic Settlement + Consolidation Settlement

$$S_{total} = S_e + S_c$$

Elastic Settlement also called immediate Settlement occurs in sandy, silty and clayey soils.

Consolidation Settlement depends on the following:

1. **Cohesive soils** due to the expulsion of the water from the voids.
2. **Soil permeability** the rate of settlement may varied from soil to another.
3. **Variation in the rate of consolidation** settlement depends on the boundary conditions.

Consolidation Settlement
(Time Dependent Settlement)

Consolidation = Primary consolidation + Secondary Consolidation

Primary consolidation - Volume change in soil is due to reduction in pore water pressure

Secondary Consolidation - Volume change is due to the rearrangement of the soil particles

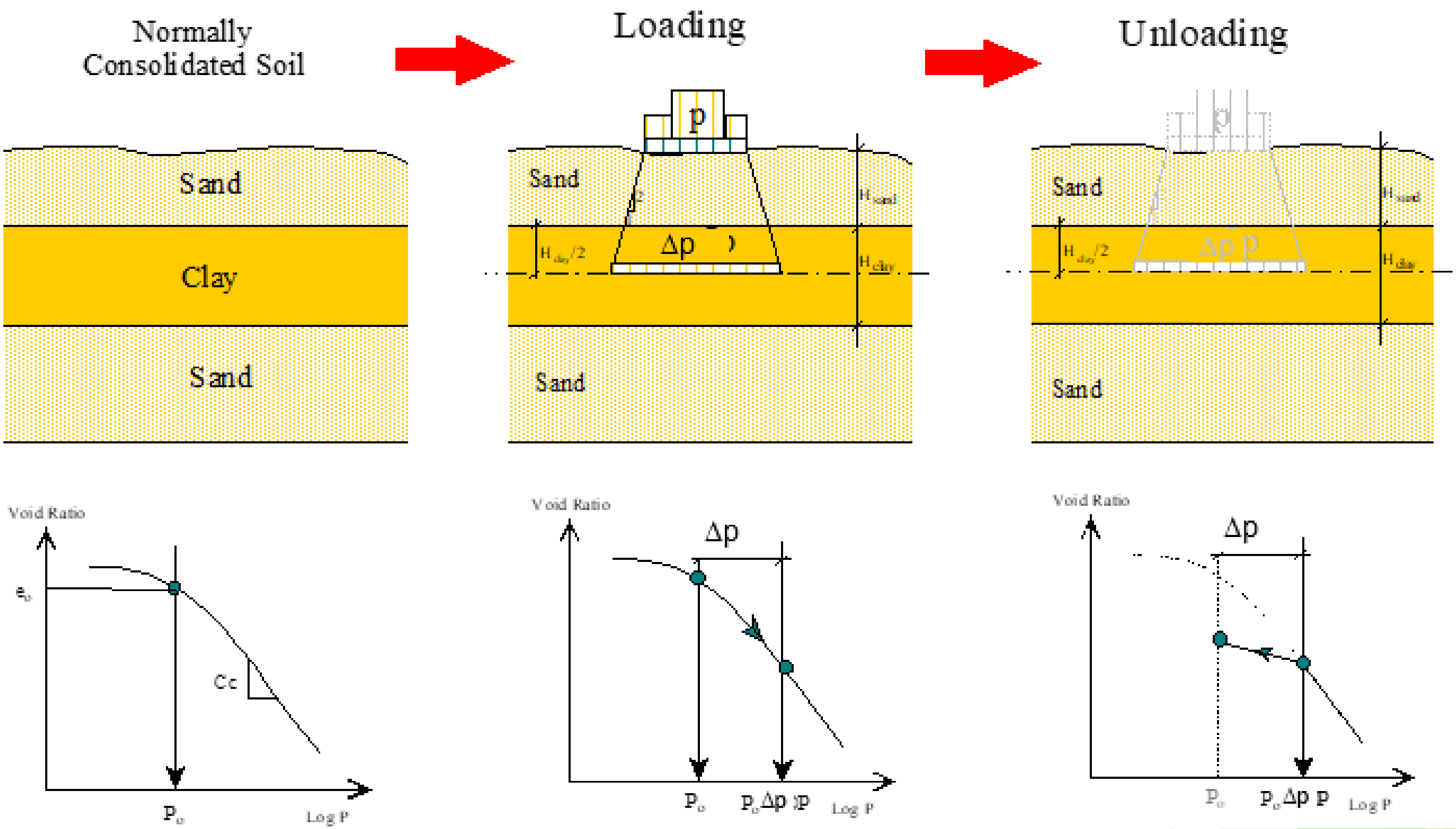
After the primary consolidation no pore water pressure change, $\Delta u = 0$ then secondary consolidation occurs.

Primary Consolidation Settlement

Primary Consolidation Settlement is of two types:

1. **Normal Consolidated Soil** - A soil that is currently experiencing its highest stress.
   Such soils are more compressible representing high settlement of loading.
1. **Overconsolidated Soil** - A soil which are loaded in the past history and past load was more than present effective stress. Such soils are less compressible and more stable.

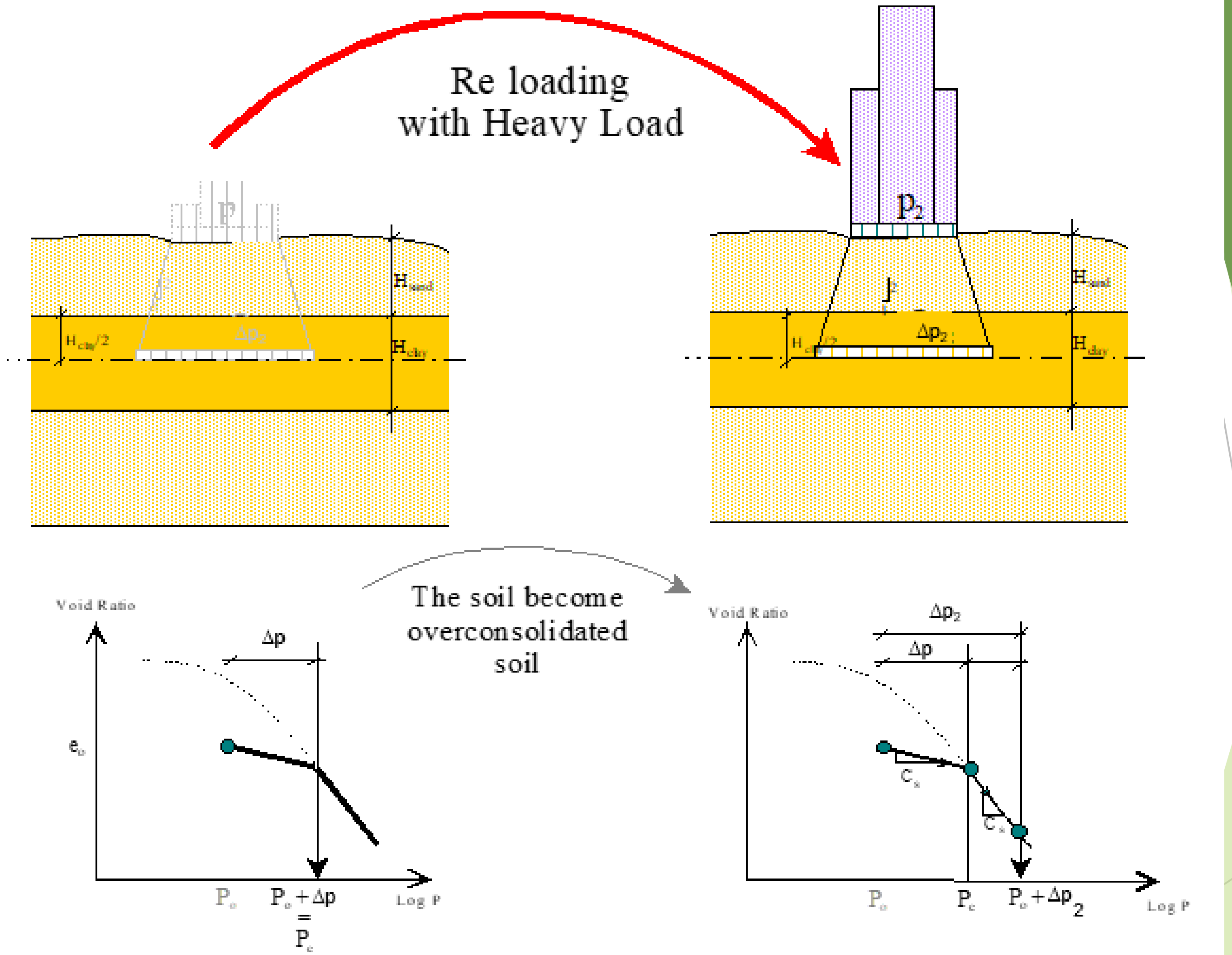
Normally Consolidate Soil



$$\Delta H = \frac{Cc\,H}{1 + e_O} \log \left(\frac{P_o + \Delta P}{P_0} \right)$$

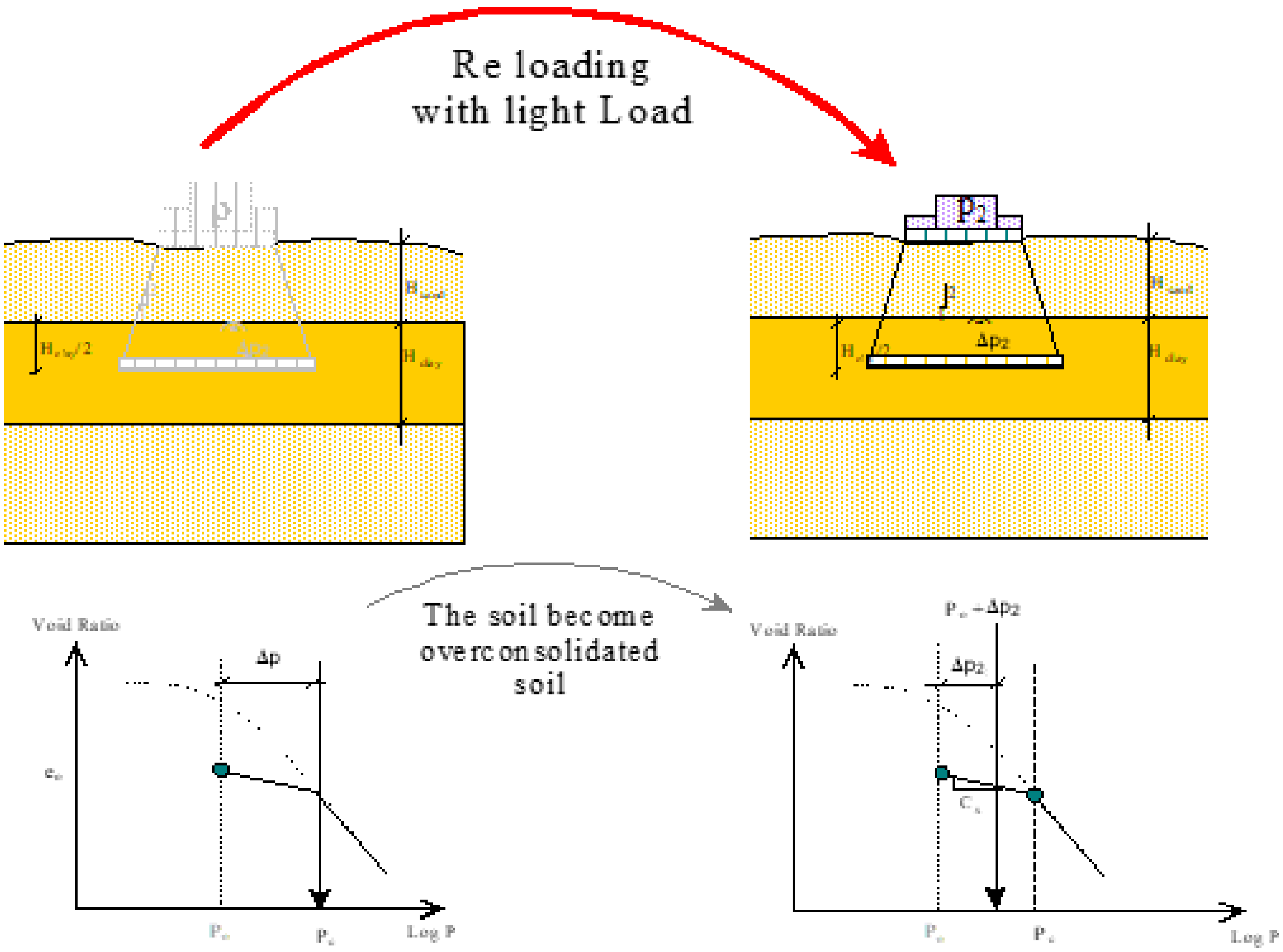
These graphs are determined through **Oedometer Test** on sample of clay where we want to determined settlement

Over Consolidated Soil



$$\Delta H = \frac{C_s H}{1 + e_o} \log\left(\frac{P_c}{P_o}\right) + \frac{C_c H}{1 + e_o} \log\left(\frac{P_o + \Delta P_2}{P_c}\right)$$

Over Consolidated Soil



$$\Delta H = \frac{C_s H}{1 + e_o} \log \left(\frac{P_o + \Delta P_2}{P_o} \right)$$

Overconsolidation Ratio

Maximum past pressure (s'$_p$) quantifies The "stress history" of the soil - it is the largest magnitude of effective stress the soil has been consolidated to in the past.

Overconsolidation Ratio (OCR) quantifies the magnitude of a soil's existing state of stress relative to its maximum past stress.

$$OCR = \frac{\sigma'_p or\ P_o}{\sigma'}$$

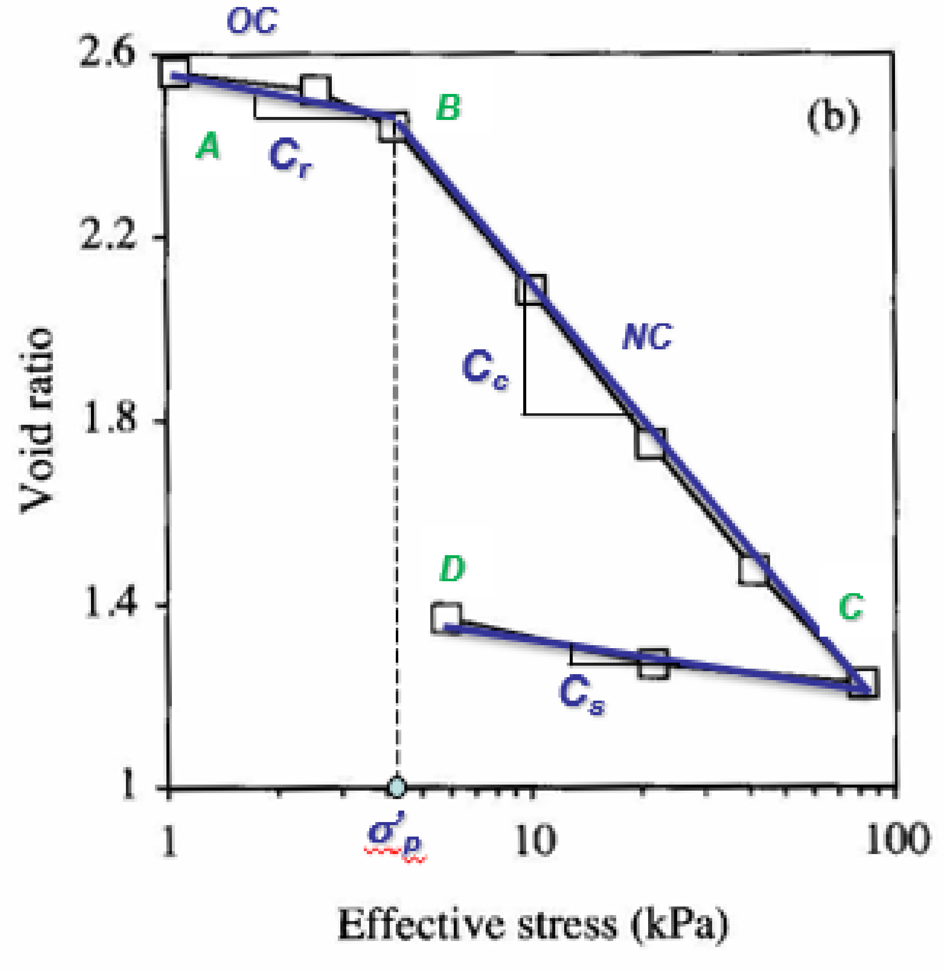
If OCR = 1, then $\sigma'_p = \sigma'$ and the soil is "normally consolidated" (soft response - virgin compression)

If OCR > 1, then $\sigma'_p > \sigma'$ and the soil is "over consolidated" (stiff response - it has been precompressed)

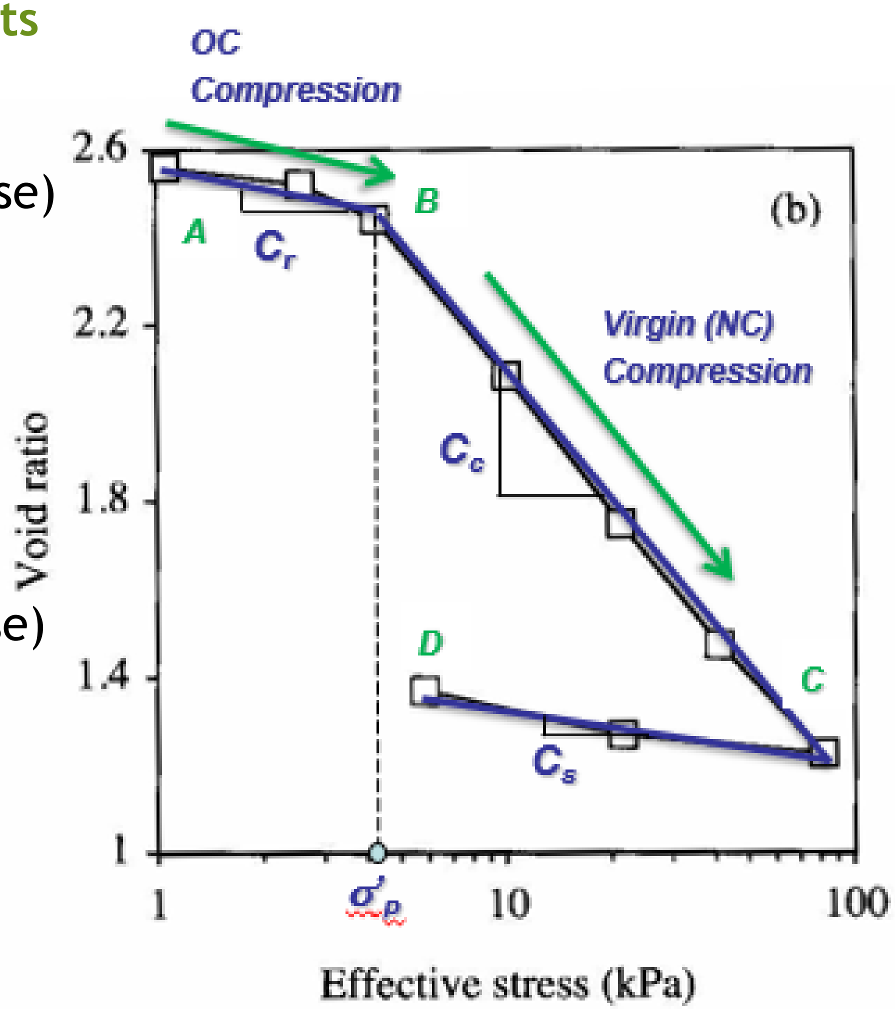
Sources of Overconsolidation:

- Extensive erosion
- Past glacial activity
- Removed structures
- Risen water table
- Evaporation

This graph is received from Consolidation (Oedometer) Testing.



- **Divide e-log p curve into linear segments**
- OC = Overconsolidated (stiff response)
- NC = Normally Consolidated (soft response)
- OC and NC portions separated by s'$_p$
- P_o or σ'_p = "maximum past pressure"
- C_r = Recompression Index (slope of OC)
- C_c = Compression Index (slope of NC)
- C_s = Swell Index (slope of unload response)



$$C_r = -\left.\frac{\Delta e}{\Delta \log(\sigma')}\right|_{A\to B}$$ ***0.01 ~ C_r ~ 0.5***

$$C_c = -\left.\frac{\Delta e}{\Delta \log(\sigma')}\right|_{B\to C}$$ ***0.1 ~ C_c ~ 2.6***

$$C_s = -\left.\frac{\Delta e}{\Delta \log(\sigma')}\right|_{C\to D}$$

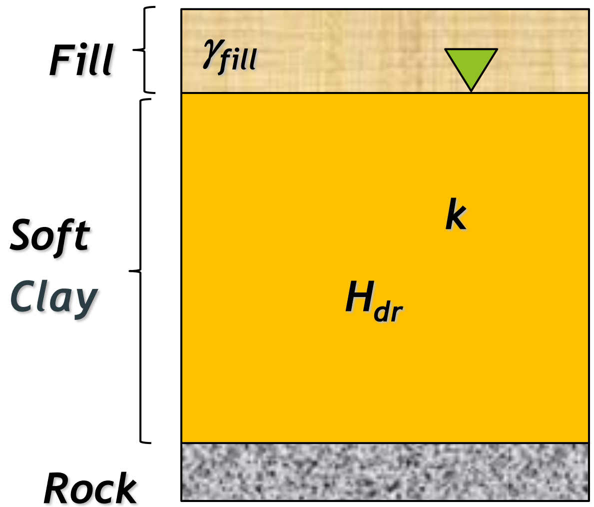
$$C_c > C_r$$

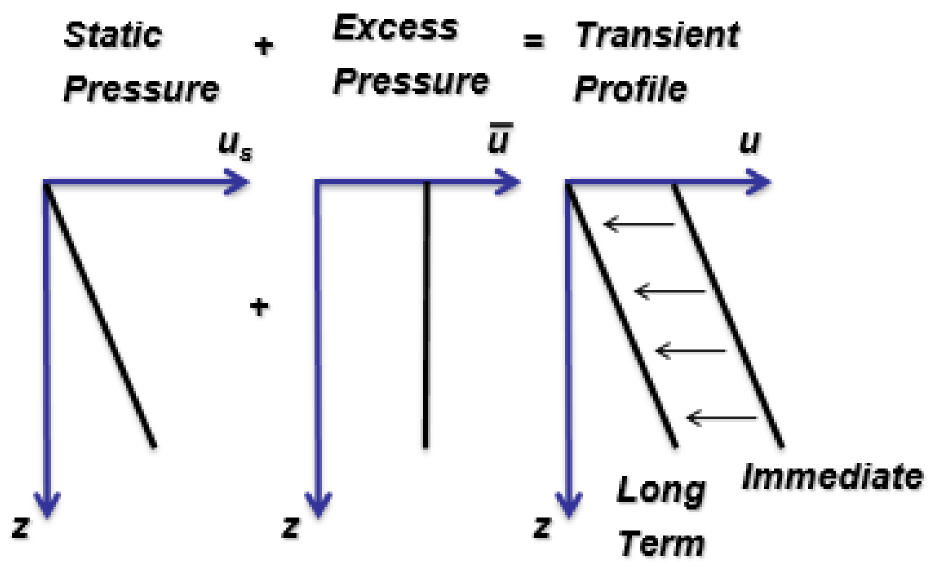
$$C_r \approx C_s$$

$$\Delta H = \frac{C_r H}{1+e_0}\left[\log\left(\frac{\sigma'_p}{\sigma'_i}\right)\right] + \frac{C_c H}{1+e_0}\left[\log\left(\frac{\sigma'_f}{\sigma'_p}\right)\right]$$

Rate of Consolidation Settlement

- Recall that consolidation is volume change due to pore water being squeezed out
- Dissipation of excess pore pressure
- So consolidation takes time!!! - depends on:
  - Hydraulic conductivity (k)
  - Drainage boundaries (max length of drainage path, H_{dr})





Drainage Path Length,Hdr

$$Q = k \frac{dh_t}{dL} A$$ → *Flow rate (rate of consolidation) depends on k and dh_t/dL*

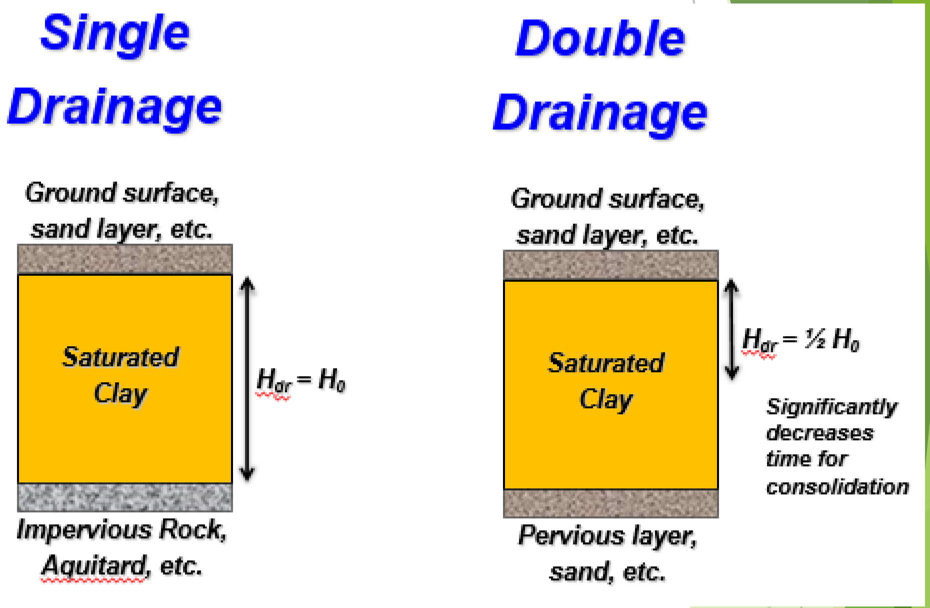
Settlement at any time = S_{time}

Stime = Sultimate*U%
U% = f(Tv)……..Tv = Time factor (Adopted from table)

Tv = f(cv) …….cv = Coefficient of Consolidation (obtained from Laboratory test)

$Tv = cv.t/(Hdr)^2$

t = time (days, months or years)
Hdr = Drainage path H or H/2



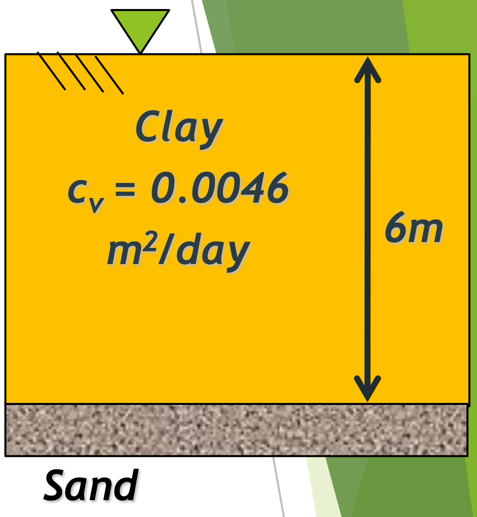
Once you determine Tv, use the table shown on the page to determined U%

Degree of Consolidation (U%) Vs. Time Factor (Tv)

U (%)	T_v	U (%)	T_v	U (%)	T_v	U (%)	T_v
0	0	26	0.0531	52	0.212	78	0.529
1	0.00008	27	0.0572	53	0.221	79	0.547
2	0.0003	28	0.0615	54	0.230	80	0.567
3	0.00071	29	0.0660	55	0.239	81	0.588
4	0.00126	30	0.0707	56	0.248	82	0.610
5	0.00196	31	0.0754	57	0.257	83	0.633
6	0.00283	32	0.0803	58	0.267	84	0.658
7	0.00385	33	0.0855	59	0.276	85	0.684
8	0.00502	34	0.0907	60	0.286	86	0.712
9	0.00636	35	0.0962	61	0.297	87	0.742
10	0.00785	36	0.102	62	0.307	88	0.774
11	0.0095	37	0.107	63	0.318	89	0.809
12	0.0113	38	0.113	64	0.329	90	0.848
13	0.0133	39	0.119	65	0.304	91	0.891
14	0.0154	40	0.126	66	0.352	92	0.938
15	0.0177	41	0.132	67	0.364	93	0.993
16	0.0201	42	0.138	68	0.377	94	1.055
17	0.0227	43	0.145	69	0.390	95	1.129
18	0.0254	44	0.152	70	0.403	96	1.219
19	0.0283	45	0.159	71	0.417	97	1.336
20	0.0314	46	0.166	72	0.431	98	1.500
21	0.0346	47	0.173	73	0.446	99	1.781
22	0.0380	48	0.181	74	0.461	100	∞
23	0.0415	49	0.188	75	0.477		
24	0.0452	50	0.197	76	0.493		
25	0.0491	51	0.204	77	0.511		

Examples

Example 1: How long for 90% consolidation?



$$U = 0.90$$

From Table in previous page,
T = 0.848

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

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

$$t = \frac{(0.848)(3)^2}{0.0046\ m^2/day}$$

$$= 1660 days$$

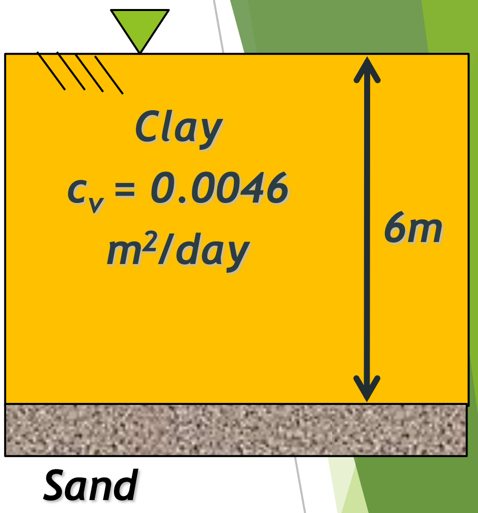
$$t = 4.6 years$$

Examples

If S_∞ = 1.24m, how long for 0.635m of settlement?

$$U = \frac{S_t}{S_\infty} = \frac{0.635}{1.24} = 0.5 \quad (50\%)$$

From table, T = 0.196

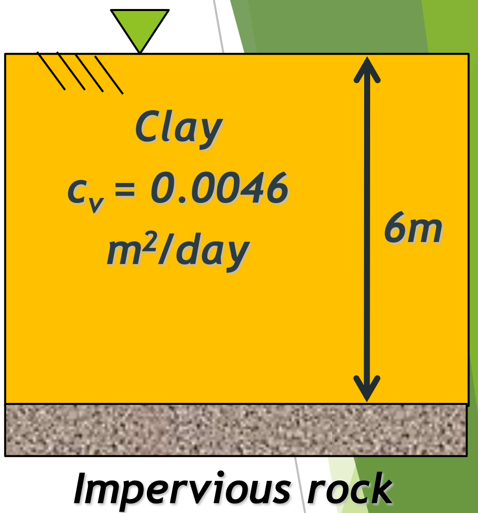


$$T = \frac{c_v t}{(H_{dr})^2} = 0.196$$
$$t = \frac{(0.196)(H_{dr})^2}{c_v}$$
$$t = \frac{(0.196)(3)^2}{0.0046\ m^2/day} = 384 days$$
$$t = 1.05 years$$

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

$$U = 0.90$$

From table, T = 0.848



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

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

$$t = \frac{(0.848)(6)^2}{0.0046\ m^2/day} = 6634 days$$

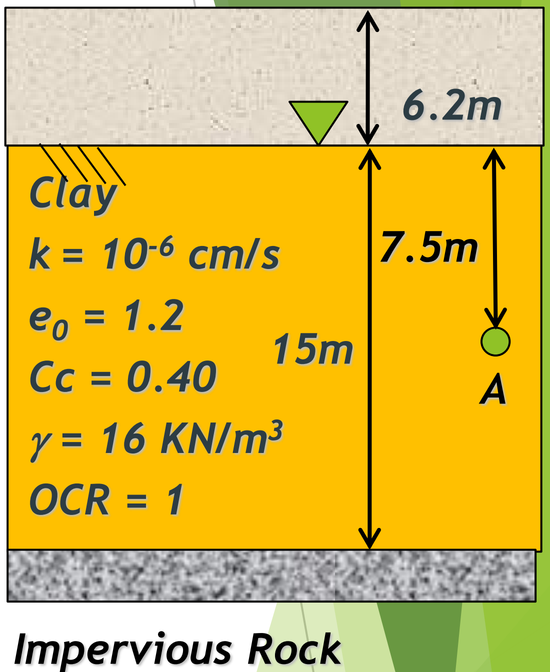
$$t = 18.2 years \ !!!!!!$$

Compute total consolidation settlement and time for 95% consolidation

OCR = 1, so clay is NC.

$$\sigma'_i = \sigma'_p$$

Analyze using Point A at midpoint of clay



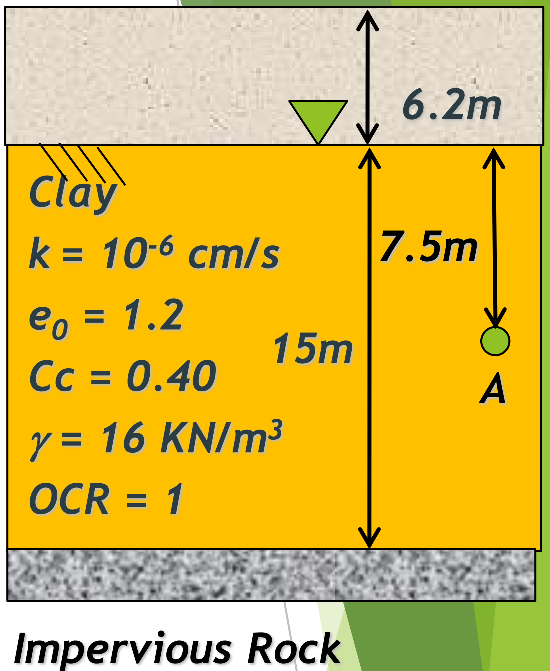
$$\sigma'_{A_i} = (16)(7.5) - (9.81)(7.5) = 46.4\ KN/m^2$$

$$\sigma'_{A_f} = 46.4 + (16)(6.2) = 145.6\ \frac{KN}{m^2}$$

$$S_\infty = \Delta H = \frac{C_c H}{1 + e_o} \log\left(\frac{\sigma'_{A_f}}{\sigma'_{A_i}}\right)$$

$$S_\infty = \frac{(0.4)(15)}{1 + 1.2} \log\left(\frac{145.6}{46.4}\right) = 1.35m$$

Not given c_v, so need to calculate…



$$c_v = \frac{k}{m_v \gamma_w}$$

$$m_v = \frac{d\varepsilon}{d\sigma'} = \frac{\Delta H / H_0}{\Delta\sigma'} = \frac{1.35/15}{99.2} = 9.07 \times 10^{-4} \frac{m^2}{KN}$$

so

$$c_v = \frac{(10^{-8} m/s)(86{,}400 s/day)}{(9.07 \times 10^{-4})(9.81)} = 0.0971\ m^2/day$$

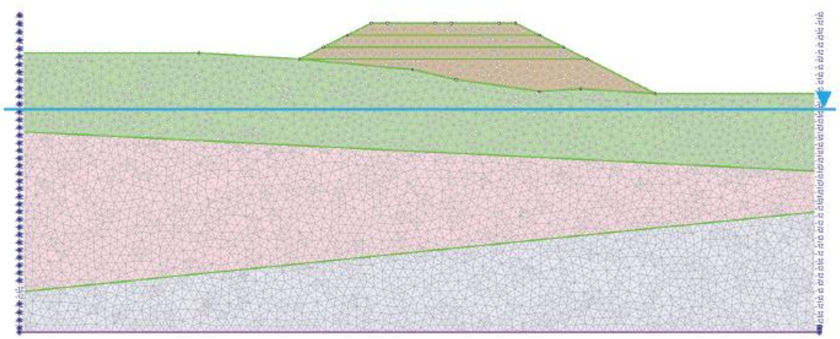
If U = 95%, T = 1.129

$$t = \frac{T(H_{dr})^2}{c_v} = \frac{(1.129)(15)^2}{0.0971} = 7.1\ years$$

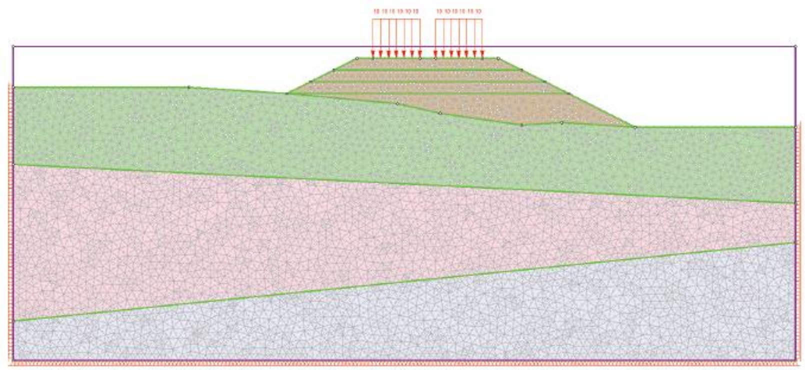
$$S_t = (U)(S_\infty) = (0.95)(1.35) = 1.28m$$

Numerical Analysis

This example I took from Rocscience RS2 Tutorials. This example will show how the fill of road embankment and later the traffic load generates excess pore water pressure and consolidation settlement from the time of start of construction will become negligible with the time.
This process is of 65days. This process also shows the dissipation of excess pore pressure as well with the passing of days.

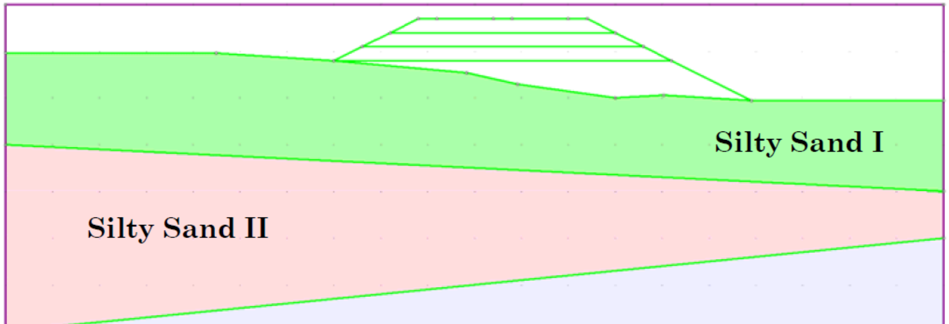


Embankment tutorial– groundwater boundary conditions

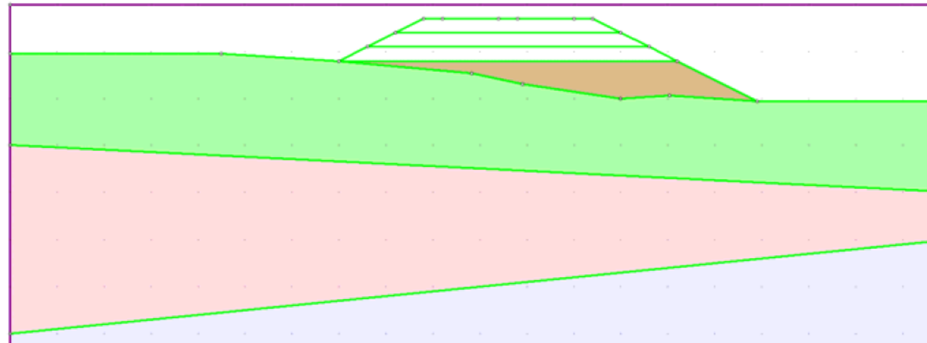


Embankment tutorial – loading and external boundaries

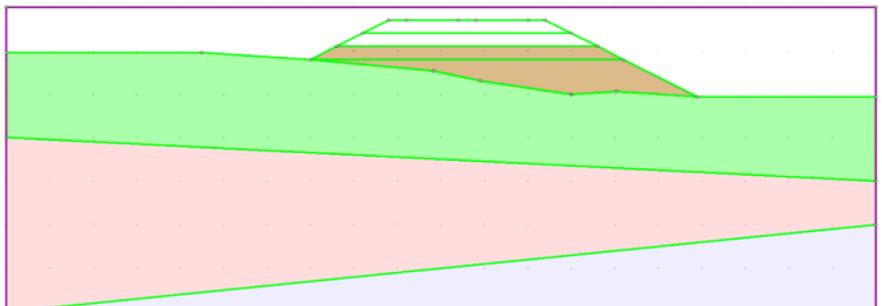
Numerical Analysis – Stages of Loading



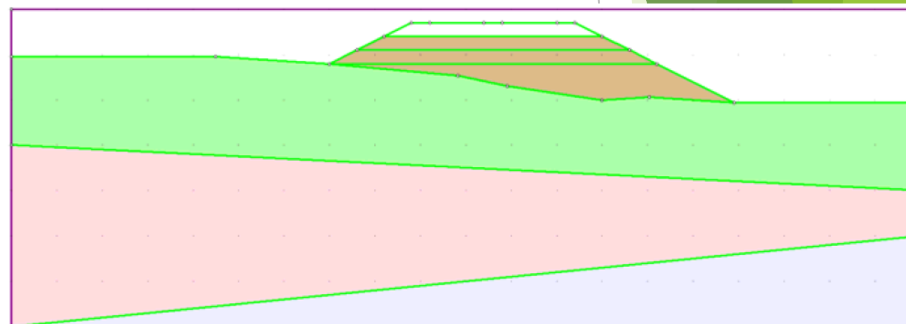
Stage 1 – Actual Soil Profile (0 day)



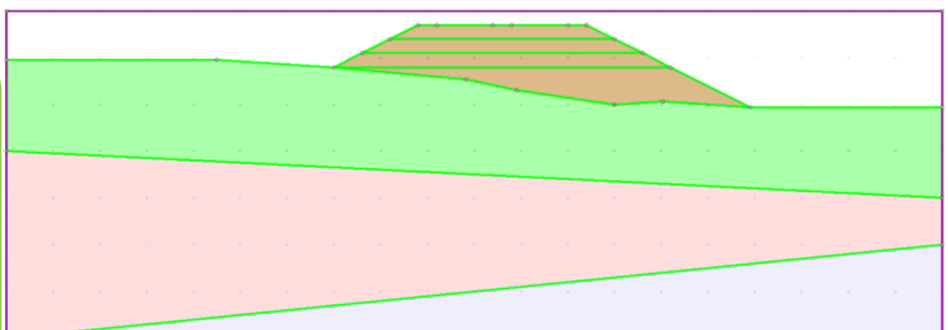
Stage 2 – 1st layer of Embankment fill (day -1)



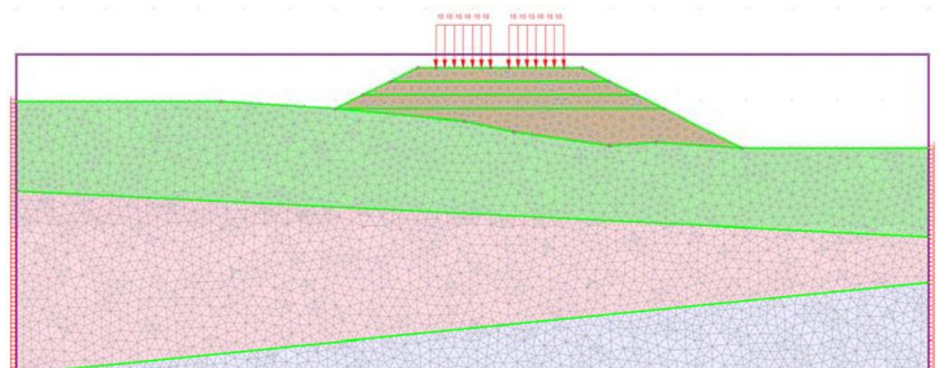
Stage 3 – 2nd layer of Embankment fill (day -10th)



Stage 4 – 3rd layer of Embankment fill (day 20th)



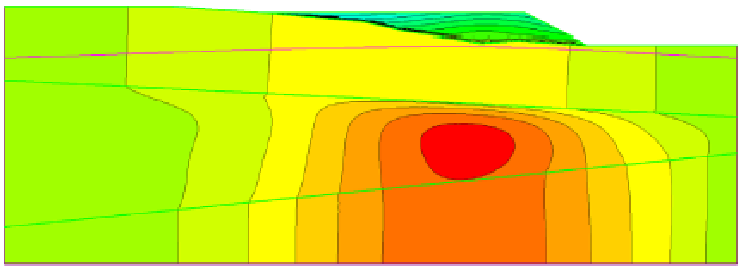
Stage 5 – 4th layer of Embankment fill (day 60th)



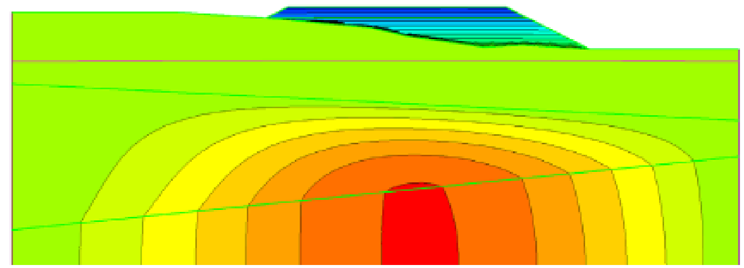
Stage 6 – Vehicular Loding (day 60th onwards till day 65)

Results

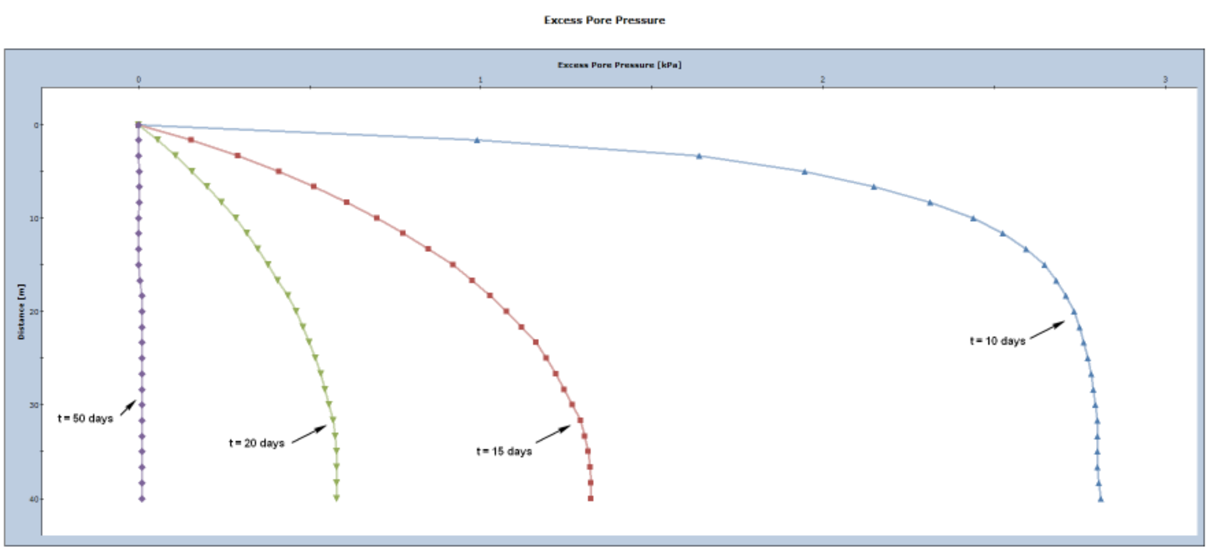
Excess Pore Pressure



Excess pore water pressure at t=1 days

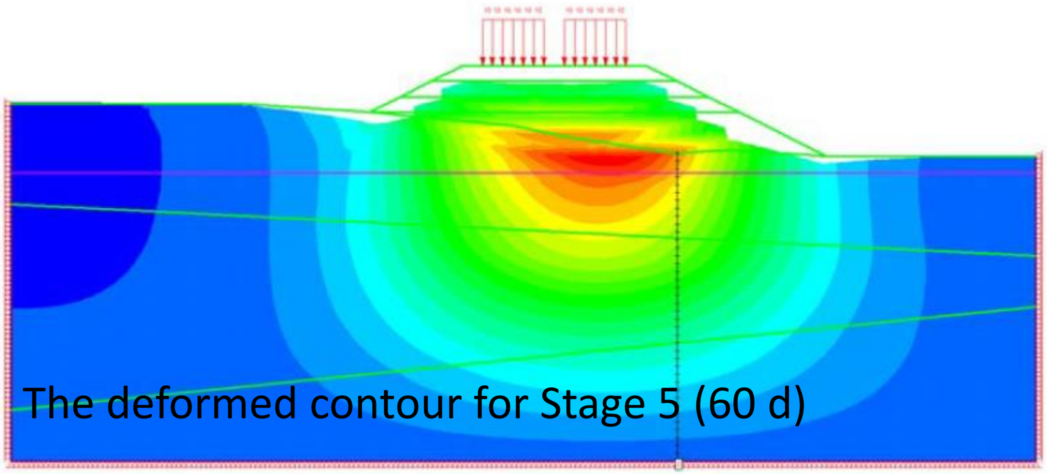


Excess pore water pressure at t=10 days

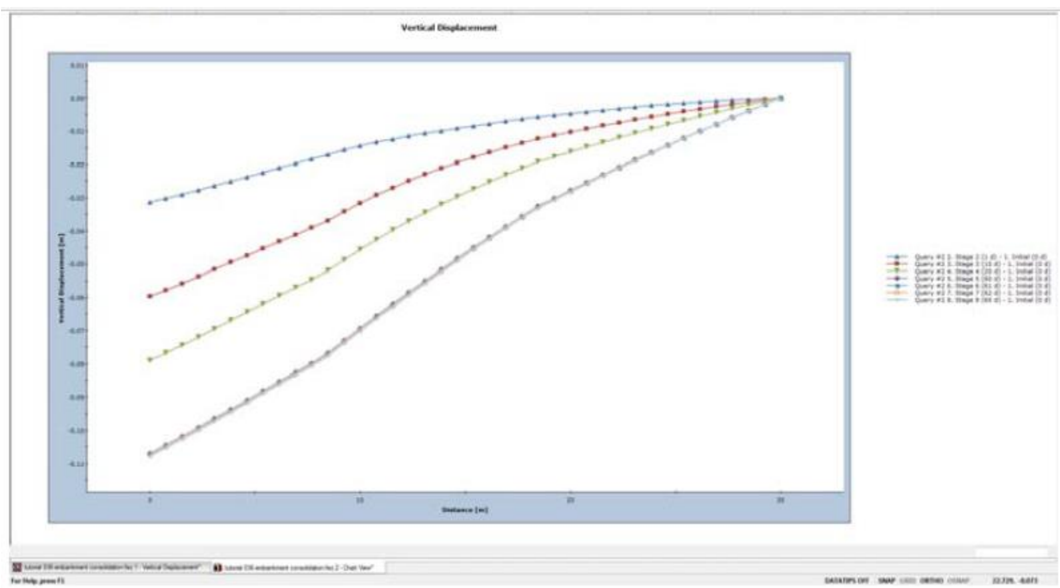


Excess Pore Pressure vs Depth (line for each stage)

Result - Settlement



The deformed contour for Stage 5 (60 d)



The vertical settlement underneath the embankment increases until stage 5 (addition of traffic loads) and then stays constant for the remaining stages.

Any Questions
Please write in the comments below

Thankyou for
Your Time and Patience