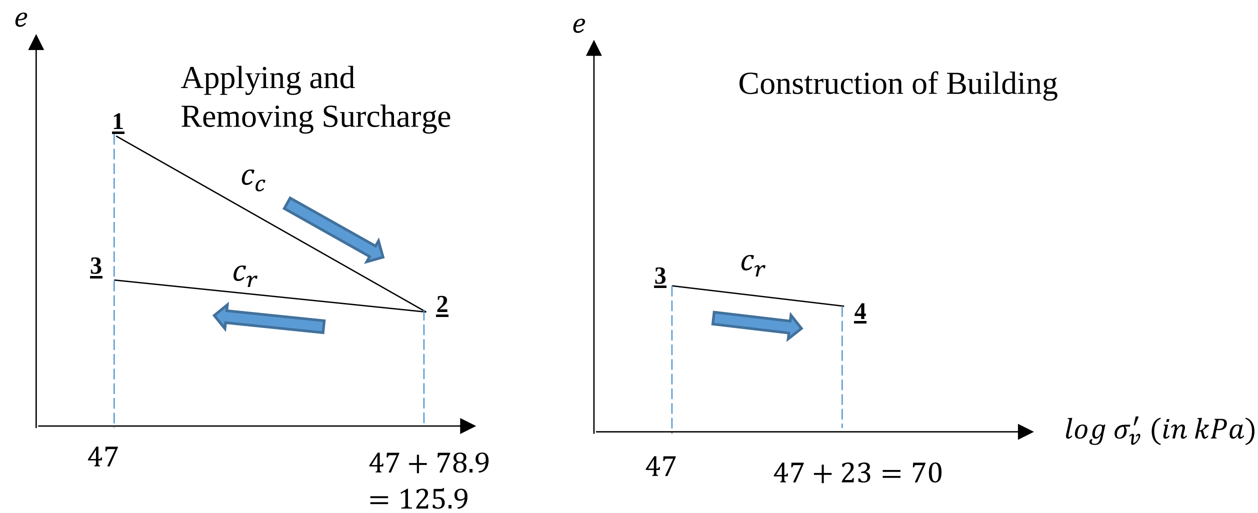
1) (2 points) For the example on page 22/24 of the class notes pdf, after the wide fill surcharge of 78.9 kPa is applied at the ground surface for 9 months, then the surcharge is removed and the building is constructed. Ignore the time for removal of surcharge and time for construction of building, assume they are done instantaneously. Calculate the amount of primary consolidation settlement expected under the building load and calculate the time required for this much settlement to take place.

Note that: You can think that building will be constructed immediately after removing the surcharge. Therefore vertical stresses will be dropping from 125.9 kPa to 70 kPa directly. **In that case, settlement will be 0**. Indeed, there will be some swelling.

After removing the surcharge, if you wait for some time for swelling of soil and then construct your building, the clay layer will be compressed along the recompression range and the solution will be:



$$S_c = H * \frac{C_r}{1+e} * log\left(\frac{\sigma_{4'}}{\sigma_3'}\right) = 5 * \frac{0.105}{1+0.9} * \log\left(\frac{70}{47}\right) = \mathbf{4.8\ cm}$$

- We ignored the change in initial void ratio, e (more accurate solution can consider a new void ratio after removal of surcharge)
- C_r / C_c ratio typically 0.1 to 0.2

$$C_r = C_c * 0.1 = 0.7 * 0.15 = 0.105$$

- c_v in recompression range is 5 to 10 times c_v in compression range

$$c_v = 7.5 * 0.36 \frac{\text{m2}}{\text{month}} = 2.7 \frac{\text{m2}}{\text{month}}$$

$$T_v = \frac{(c_v * t)}{d^2} \rightarrow \quad (U = 95\%)\ 1.129 = \frac{2.7 * t}{5^2} \rightarrow t$$

$$= \mathbf{10.5\ months}$$

2) (13 points) A borehole log is given on the next page. Borehole is conducted to a depth of 15.45 m, and below that depth, we do not have any information about the subsoils. A 2-m-high embankment (having 7 m base width and 3 m top width) composed of gravel with unit weight of 21 kN/m3 is to be placed at the ground surface. Use Boussinesq stress distribution under the embankment (hint: page 3/26 of the class notes pdf), and coefficient of volume compressibility, mv. To convert SPT-N values to N60 , in Turkey, use the correlation: N60 = N x 0.75. Coefficient of consolidation, cv, values for ML, CL and CH soils at this site, are estimated as 0.4, 0.8 and 0.55 m2/month, respectively. For all unknown information, make reasonable assumptions using your engineering judgement and write in your solution.
a) Calculate and plot settlement (under the center of the embankment at the original ground surface) versus time, expected under this embankment load.

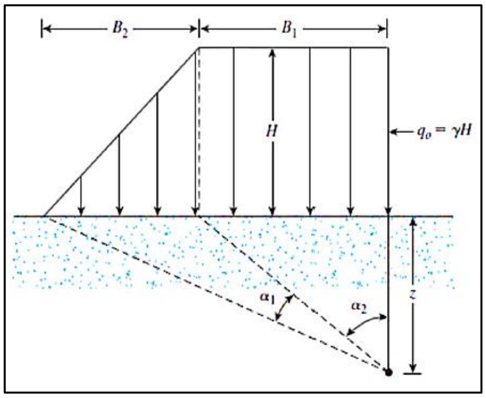
Time dependent consolidation settlement occurs with dissipation of excess water pressure. You should consider only ML, CL and CH layers in the time dependent settlement calculations. In SM (sand) and GM (gravel) only immediate (elastic) settlement is expected and it is not calculated.

Note that, we can calculate the depth of soil that will be affected by the embankment loading, by calculating the vertical stress increase under the centerline of the embankment with depth. By using the equation for vertical stress increase given on the next page, we will see that at 15.6 m depth from ground surface 20% of the embankment load (γH) will be acting, and at 31.6 m depth from ground surface 10% of the embankment load will be acting. Therefore we see that **it is sufficient to calculate settlements to a depth of 15.45 m**.

$$S = \sum H * m_v * \Delta\sigma'$$

CL layer is 6 m thick. We noted in lecture notes that if a clay layer is thicker than 6 m we should subdivide the clay to obtain more accurate calculations. **Since this clay layer's thickness is 6 m, you may subdivide this layer, or you may consider as one 6-m thick layer, both solutions are possible and will be accepted for this HW** (however keep in mind that subdividing the clay layer gives more accurate results). We will show the solution for subdividing the CL layer into two equal-thickness sublayers.

For ML, CL-1, CL-2 and CH, stress increase should be found at the mid-depth of each layer by using Boussinesq stress distribution.



$$\Delta\sigma = \frac{q_0}{\pi}\left[\left(\frac{B_1+B_2}{B_2}\right) * (\alpha_1 + \alpha_2) - B_1/B_2(\alpha_2)\right]$$

$$\alpha_1 = \tan^{-1}\frac{B_1 + B_2}{z} - \tan^{-1}\frac{B_1}{z}$$

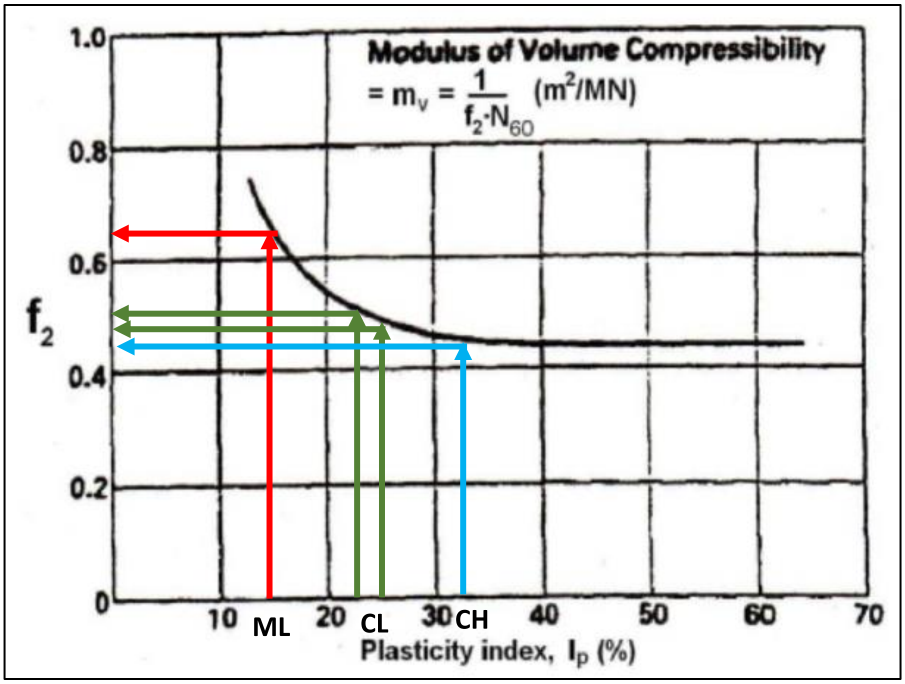
$$\alpha_2 = \tan^{-1}\frac{B_1}{z}$$

Note that: To find $\Delta\sigma$ at the mid-depth of each layer, you should multiply the stresses by 2 because the above formulation is for half of the embankment (symmetrical at the centerline).

q_o (kN/m²)	42
B_1(m)	1.5
B_2(m)	2

Layer	Mid-depth (m)	α_1	α_2	$\Delta\sigma$ (kN/m²)
ML	3.35	0.3863	0.4210	29.3
CL-1	8.2	0.2225	0.1809	15.2
CL-2	11.2	0.1697	0.1331	11.5
CH	14.075	0.1376	0.1062	9.3

Now, to calculate settlement, you need to find coefficient of volume compressibility, m_v.



Layer	PI_{ave} (%)	f_2	N_{ave}	$N_{60} = 0.75 * N_{ave}$	m_v ($\frac{m^2}{MN}$)
ML	15	0.66	8	6	0.253
CL-1	22	0.51	10.5	8	0.245
CL-2	25	0.49	10.5	8	0.255
CH	32	0.45	9	7	0.317

Calculate total (primary) settlement of each layer and time of total settlement (time for 95% average degree of consolidation) for each layer.

For ML layer, water can dissipate through sand at the top and gravel at the bottom. Therefore, **ML layer has two way drainage**.

For maximum drainage distances of other layers, different assumptions and justifications could be possible using your engineering judgment.

(1) CL+CH layers can be considered together as one layer (that is 8.75 m thick) just to calculate the degree of consolidation (settlement of CL and CH can be calculated separately). We could use a weighted average c_v value ($c_{v\,(CL+CH)}$ = (0.8 x 6 m + 0.55 x 2.75 m) / (8.75 m) = 0.72 m^2/month). And we would consider CL+CH layers can drain only one way through the gravel layer above. CL and CH each will have this value of degree of consolidation, U.

(2) If we treat CL and CH layers as two different layers:

a. CL layer can be considered to be drainable from top through gravel layer above and drainable from bottom through CH underneath, since the CH layer underneath is described as it has “sand bands”, and it is a “silty” clay, in the borehole log. Someone can argue that CL should be considered one-way drainable, i.e. non-drainable from the bottom, because this is the worst-case scenario and settlements will take longer time. However, this is not in agreement with the borehole log descriptions at the site).

b. CH layer can be consider as one-way drainable from the top, because: (i) if we consider CH not drainable from top, and not drainable from bottom, there won’t be any consolidation settlement, just there will be built-up of excess pore water pressure in CH (which will not be able to dissipate anywhere). Therefore considering at least one way drainage will mean that we will have consolidation settlement in CH layer. (ii) we don’t know whether there is a permeable or impermeable layer at the bottom of CH since borehole ends at 15.45 m. So making any assumptions about the bottom boundary is open to discussion.

(3) In this HW solution, we will consider CL-1 one-way drainable through gravel layer. For CL-2 and CH, we will assume they are one-way drainable. Other assumptions are possible with proper justifications.

Layer	Layer thickness, H (m)	Max. drainage distance, d (m)
ML	3.7	1.85
CL-1	3	3
CL-2	3	3
CH	2.75	2.75

$$S_{total} = \sum H * m_v * \Delta\sigma'$$

$$t = (T_v * d^2)/c_v$$

Layer	$\boldsymbol{S_{total}}$ **or** $\boldsymbol{S_{U=95\%}}$ $\boldsymbol{(mm)}$	$\boldsymbol{t_{total}}$ **or** $\boldsymbol{t_{U=95\%}}$ **(month)**
ML	27.4	9.66
CL-1	11.2	12.70
CL-2	8.8	12.70
CH	8.1	15.52

$$S_{total} = 55.5\ mm$$

For every month, you can calculate the average degree of consolidation of each layer and how much settlement will be completed for each layer. Then, you should sum the contributions and plot settlement versus time. In the calculation of U%, don't forgot that the formulation of U changes at U=60% level.

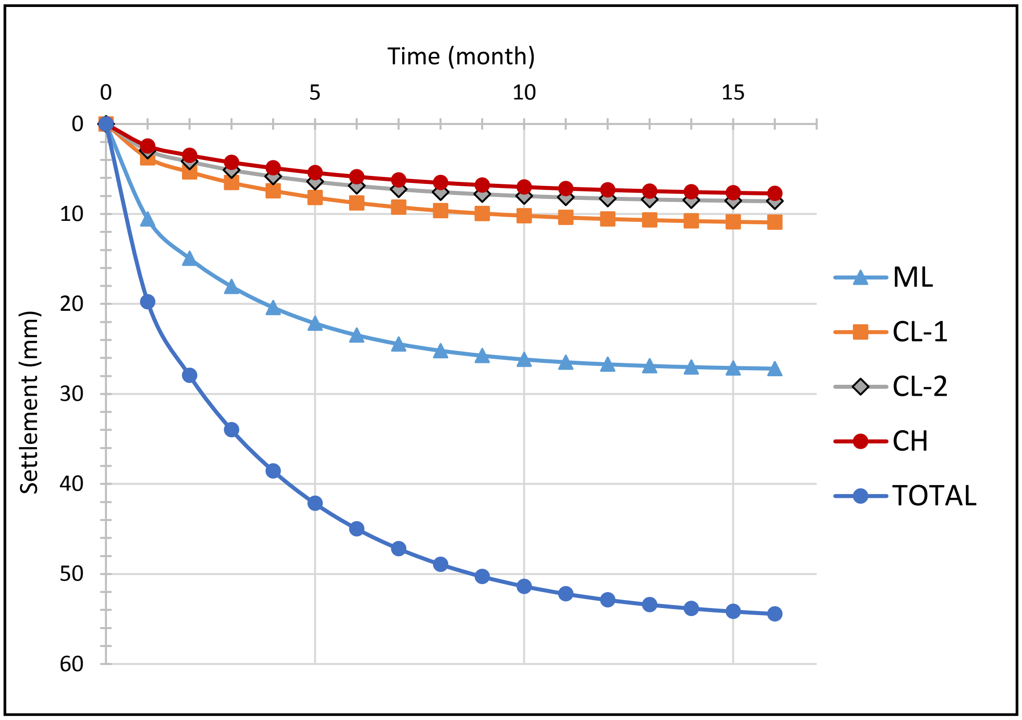
	ML		
time (month)	T_v	U	S_t (mm)
0	0.000	0.000	0.000
1	0.117	0.386	10.572
2	0.234	0.546	14.951
3	0.351	0.659	18.053
4	0.467	0.744	20.397
5	0.584	0.808	22.153
6	0.701	0.856	23.469
7	0.818	0.892	24.456
8	0.935	0.919	25.195
9	1.052	0.940	25.749
10	1.169	0.955	26.164
11	1.286	0.966	26.476
12	1.402	0.975	26.709
13	1.519	0.981	26.884
14	1.636	0.986	27.015
15	1.753	0.989	27.113
16	1.870	0.992	27.186

	CL-1		
time (month)	Tv	U	St (mm)
0	0.000	0.000	0.000
1	0.089	0.336	3.772
2	0.178	0.476	5.334
3	0.267	0.583	6.533
4	0.356	0.663	7.432
5	0.444	0.729	8.177
6	0.533	0.783	8.775
7	0.622	0.825	9.255
8	0.711	0.860	9.640
9	0.800	0.887	9.950
10	0.889	0.910	10.198
11	0.978	0.927	10.398
12	1.067	0.942	10.558
13	1.156	0.953	10.687
14	1.244	0.962	10.791
15	1.333	0.970	10.874
16	1.422	0.976	10.940

	CL-2		
time (month)	Tv	U	St (mm)
0	0.000	0.000	0.000
1	0.089	0.336	2.961
2	0.178	0.476	4.188
3	0.267	0.583	5.129
4	0.356	0.663	5.835
5	0.444	0.729	6.420
6	0.533	0.783	6.889
7	0.622	0.825	7.266
8	0.711	0.860	7.569
9	0.800	0.887	7.812
10	0.889	0.910	8.007
11	0.978	0.927	8.164
12	1.067	0.942	8.290
13	1.156	0.953	8.391
14	1.244	0.962	8.472
15	1.333	0.970	8.537
16	1.422	0.976	8.590

	CH		
time (month)	Tv	U	St (mm)
0	0.000	0.000	0.000
1	0.073	0.304	2.464
2	0.145	0.430	3.485
3	0.218	0.527	4.268
4	0.291	0.605	4.895
5	0.364	0.670	5.421
6	0.436	0.724	5.861
7	0.509	0.769	6.228
8	0.582	0.807	6.535
9	0.655	0.839	6.792
10	0.727	0.865	7.007
11	0.800	0.887	7.186
12	0.873	0.906	7.336
13	0.945	0.921	7.461
14	1.018	0.934	7.565
15	1.091	0.945	7.653
16	1.164	0.954	7.726

time (month)	Stotal (mm)
0	0.000
1	19.770
2	27.958
3	33.984
4	38.559
5	42.171
6	44.994
7	47.205
8	48.940
9	50.303
10	51.377
11	52.223
12	52.893
13	53.422
14	53.843
15	54.176
16	54.442



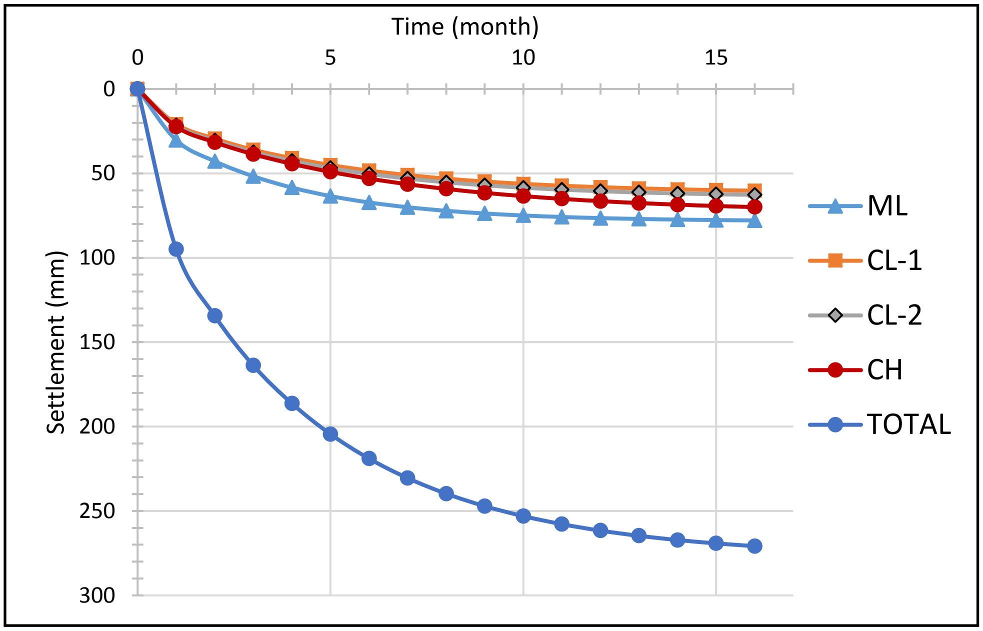
b) A colleague suggests to do preloading by applying a very wide fill of 4-m-height (21 kN/m^3) at ground surface. Make calculations and determine how long such a fill should be kept at ground surface for the preloading method to work properly.

You can solve this part by two different approaches. First approach is repeating part (a) and plot a new settlement versus time plot. And then, you can get time corresponding to settlement in part-a, 55.52 mm. Second approach is writing an equation which has only one unknown, time.

First approach:

If you repeat part (a) and plot settlement versus time, you get the following plot (although settlement of individual layers is not asked in the question).

month	St_{total}
0	0.000
1	94.997
2	134.346
3	163.801
4	186.299
5	204.464
6	218.937
7	230.488
8	239.721
9	247.112
10	253.038
11	257.797
12	261.624
13	264.705
14	267.190
15	269.196
16	270.818



You can get time corresponding to 55.5 mm settlement by linear interpolation.

$$t_{55.52mm} = \frac{1}{94.997 - 0} * 55.52 = 0.5844\, month = 17.5\, days$$

Second approach:

This time, the stress increase because of the surcharge is 84 kPa at any depth because the preloading is wide. You should calculate settlements of each layer.

$$S_{total} = \sum H * m_v * \Delta\sigma'$$

$$S_{total} = 277.87\, mm$$

The equation will be:

$$S_{desired} = U_{ML} * S_{ML} + U_{CL-1} * S_{CL-1} + U_{CL-2} * S_{CL-2} + U_{CH} * S_{CH}$$

When you consider S_{total}=277.87 mm, and $S_{desired}$=55.52 mm, you can assume that U% for each layer will be less than 60% and you can use corresponding equation for calculation of U.

$$T_v = \frac{\pi}{4} * U^2$$

$$U = \left(4 * \frac{T_v}{\pi}\right)^{0.5} = \left(4 * \frac{c_v * t}{\pi * d^2}\right)^{0.5}$$

	$S_{total}\ (mm)$
ML	78.48
CL-1	61.76
CL-2	64.29
CH	73.33

$$55.52 = \left(4 * \frac{0.4 * t}{\pi * 1.85^2}\right)^{0.5} * 78.48 + \left(4 * \frac{0.8 * t}{\pi * 3^2}\right)^{0.5} * 61.76 + \left(4 * \frac{0.8 * t}{\pi * 3^2}\right)^{0.5} * 64.29 + \left(4 * \frac{0.55 * t}{\pi * 2.75^2}\right)^{0.5} * 73.33$$

$$t = 0.34\ month = 10.2\ days$$

Calculate U% of each layer at 10.2 days and check if the assumption is correct (assumption is correct).