Geotechnics 4

Group 14

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1. Introduction

The client wishes to construction an embankment for a motorway. The client has also requested our geotechnical services to ensure the clay, which the embankment will be constructed on reaches a consolidation of 90%. This 90% consolidation of the clay layer must be achieved within 12 months.

We propose a staged construction methodology, along with the use of prefabricated vertical drains and the addition of soil surcharge to increase the rate of consolidation.

Throughout this staged construction process, we will be working alongside a contractor who will work at a maximum rate of the 1m height increase per week (1m/week).

The results and deliverables are summarised in the following sections:

- The height of embankment at each stage of construction: Section 4
- The total primary consolidation settlement associated with each stage of construction: Section 5
- The time required for 90% completion of the total primary consolidation due to combined vertical and horizontal drainage for each stage of construction and at the end of construction: Section 6
- The incremental gain of strength at the end of each stage of construction: Section 7
- Diagram describing the variation of backfill height with time: Section 8
- Diagram describing the variation of primary consolidation with time: Section 9

1.1 Assumptions Made

This methodology assumes that when surcharge is added, e.g., 3.99m high, the settlement does not begin instantaneously, in contrast it begins ~mid-way through the construction of the embankment.

Additionally, throughout this process, the unit weight of water is $\gamma_w = 10\,{}^{kN}/_{m^3}$.

2. Total Settlement when max height of embankment is the limiting condition.

The total settlement calculation process is based on the max height allowed above ground level. In addition, when the ground consolidates, this allows additional surcharge to then be added on top. This is an iterative process which continues until convergence is achieved. The calculations are as follows:

Thickness of the clay layer: $H = 8 + \frac{14}{10} = 9.4m$

For group 14, the max height of the embankment is:

$$Max\ Height\ of\ Embankment = 7 - \frac{14}{10} = 5.6m$$

Determining the total settlement based on max height of embankment via single point iteration:

$$S_{i+1} = \frac{C_c H}{1 + e_o} log_{10}(\frac{\sigma'_0 + \Delta\sigma'}{\sigma'_0})$$

Where: $C_c = 0.9$, $H = 9.4m$, $e_o = 0.8$.

The effective stress at mid clay layer is: $\sigma'_0 = (17.5 - 10) \times \frac{9.4}{2} = 35.25\, {}^{kN}/_{m^2}$.

$$\Delta\sigma' = (5.6 + S_i) \times \gamma$$

Where $\gamma = 19.8\, {}^{kN}/_{m^3}$.

Therefore, the equation above simplifies to:

$$S_{i+1} = \frac{C_c H}{1 + e_o} log_{10}(\frac{\sigma'_0 + (5.6 + S_i) \times 19.8}{\sigma'_0})$$

Inputting our known parameters:

$$S_{i+1} = \frac{0.9 \times 9.4}{1 + 0.8} log_{10}(\frac{35.25 + (5.6 + S_i) \times 19.8}{35.25})$$

The results are as follows:

Table 1: Total settlement with maximum height of embankment

Iteration	Settlement (m)
0	0 (initial guess)
1	2.903
2	3.580
3	3.710
4	3.734
5	3.738
6	3.739
7	3.739

From this, the **Total Settlement = 3.739m**

Our client requests 90% consolidation, therefore, we want to achieve: $\sum S_i U_i = S_T \times 0.9 = 3.365m$ within 12 months.

3. Full Calculations

First of all, check the Factor of Safety for bearing capacity with maximum height of embankment. The strength of the soil is: $Cu = 20kPa,\ N_c = 5.14,\ H = 5.6m,\ \gamma = 19.8kN/m^3$

$$FS = \frac{N_c Cu}{\Delta\sigma}$$

$$FS = \frac{5.14 \times 20}{19.8 \times 5.6} = 0.927 < 1.3$$

The calculation shows that the factor of safety with maximum height of embankment is less than 1.3, which does not meet the client's requirement. In order to maintain the factor of safety above 1.3, "staged construction" has been proposed.

Staged construction:

Stage 1

Initially, the strength of the soil is: $Cu = 20kPa$. With $N_c = 5.14$, Factor of Safety limited to: $FoS = 1.3$. Apply the following equation:

$$FS = \frac{N_c Cu}{\Delta\sigma}$$

Re-arrange so $\Delta\sigma$ is the value that is being calculated:

$$\Delta\sigma = \frac{N_c Cu}{FS} = \frac{5.14 \times 20}{1.3} = 79.08kPa$$

Now the FoS has been reset back to: $FS = 1.3$.

The height which can be added in the first stage of construction is now: $\frac{79.08}{19.8} = 3.99m$

The contractor works at a rate of 1m/per week in terms of constructing the embankment height.

As a result, building 3.99m high of surcharge takes ~4 weeks.

Now calculating the settlement which can be achieved due to the surcharge:

$$S = \frac{C_c H}{1 + e_o} log_{10}(\frac{\sigma'_o + \Delta\sigma}{\sigma'_o})$$

$$where, \qquad \sigma'_o = \gamma \times {}^{Z}/_{2} = 7.5 \times {}^{9.4}/_{2} = 35.25kPa$$

$$\Delta\sigma = 79.08kPa$$

$$C_c = 0.9, \qquad H = 9.4m, \qquad e_o = 0.8,$$

$$S_1 = \frac{0.9 \times 9.4}{1 + 0.8} log_{10}\left(\frac{35.25 + 79.08}{35.25}\right) = 2.40m$$

Here the total settlement if we allow 100% consolidation is: $S_1 = 2.40m$

Calculating consolidation:

$$U = 1 - (1 - U_v)(1 - U_h)$$

$$U_h = 1 - \exp(\frac{-8T_h}{F})$$

$$F = F(n) + F_s + F_r$$

Where, $F_s = \left(\frac{k_h}{ks} - 1\right)\ln(m) = 0$, due to no smear effect.

$$k_h = 2.5 \times 5 \times 10^{-8}\, {}^{m}/_{s} = 0.0756\, {}^{m}/_{week},\ q_w = 0.0001\, {}^{m^3}/_{s} = 60.48\, {}^{m^3}/_{week}$$

$$F_r = \frac{k_h}{q_w}\pi z(2L - z) = \frac{0.0756}{60.48}\pi \times 9.4 \times (2 \times 9.4 - 9.4) = 0.347$$

$F(n)$ depends on n, $n = \frac{d_e}{d_w}$, where d_e depends on the drain influence zone, the PVD arrangement is in a square pattern with spacing 1.2m. There $d_e = 1.13 \times 1.2 = 1.356m$.

$d_w = \frac{2(w+t)}{\pi}$ from Hansbo (1979). Therefore $d_w = \frac{2(90+3)}{\pi} = 59.2mm = 0.0592m$.

Therefore, $n = \frac{1.356}{0.0592} = 22.905$.

$$F(n) = \ln(n) - 0.75 = \ln(22.905) - 0.75 = 2.38$$

Therefore, $F = 2.38 + 0.347 = 2.727$

Next, $T_h = \frac{C_h t}{{d_e}^2}$, therefore T_h is a function of time. $C_h = 2.5 \times 1.8 \times 10^{-8} = 4.5 \times 10^{-8}\, {}^{m^2}/_{s} = 0.0272\, {}^{m^2}/_{week}$.

Next, $U_v = 1 - \sum_{m=0}^{m=\infty} \frac{2}{M^2} e^{-M^2 T_v}$, where $T_v = \frac{C_v t}{{H_{dr}}^2}$, so T_v is a function of time also, H_{dr} does vary but only with each stage of construction when settlement has occurred.

For each value of t, there is a corresponding value of $U_{v,r}$, to make this process more time efficient, the relationship between t and $U_{v,r}$ has been programmed so the corresponding U can be taken for any value of time.

This proposal suggests 4 stages of construction, as a result H_{dr} will decrease slightly for each stage, as a result the relationship between t and $U_{v,r}$ must be redefined by updating H_{dr}. The corresponding graphs between time and $U_{v,r}$ for each stage have been added in the appendices section, which will be referred to throughout the rest of this document.

To summarise the optimisation process, the first stage allowed for $U1 = 70\%$. The time associated with 70% consolidation can be found through the appendices section. T=26 weeks.

As a result, at the end of stage 1 construction, $S1 = S1(\max) \times U1 = 2.402 \times 0.7 = 1.68m$.

With the client's requirement of 90% consolidation of the total settlement, the overall consolidation by the end of this stage is $U = \frac{1.68}{3.74} \times 100 = 44.92\%$.

Increase in soil shear strength is: $(\Delta C_u)_1 = 0.25 \times U_1 \times (\Delta\sigma)_1 = 0.25 \times 0.7 \times 79.08 = 13.84kPa$

Therefore, the updated $C_u = 13.84 + 20 = 33.84kPa$.

As a result, the new $FS = \frac{5.14 \times 33.84}{79.08} = 2.20$>1.3

Stage 2

With the updated shear strength of the soil, and updated factor of safety, more surcharge soil can be added.

Resetting the FoS back to 1.3:

$$\Delta\sigma = \frac{N_c Cu}{FS} = \frac{5.14 \times 33.84}{1.3} = 133.8kPa$$

Therefore, the surcharge added in stage two is: $133.8 - 79.08 = 54.72kPa$

Updating the vertical effective stress: $(\sigma_o')_2 = (\sigma_o')_1 + (U)_1 \times (\Delta\sigma')_1 = 35.25 + 0.7 \times 79.08 = 90.6kPa$

The new $H = 9.4 - 1.68 = 7.72m$, therefore $(H_{dr})_2 = 7.72m$.

The void ratio will now change in addition. $\Delta e = \frac{\Delta H}{H_O}(1 + e_O) = \frac{1.68}{9.4}(1 + 0.8) = 0.322$

Therefore, the new void ratio is: $(e_O)_2 = 0.8 - 0.322 = 0.478$

The additional settlement which can be achieved by adding the stage 2 surcharge is as follows (this is assuming U2=100%).

$$S_2 = \frac{0.9 \times 7.72}{(1 + 0.478)} \times log_{10}\left(\frac{90.6 + 54.72}{90.6}\right) = 0.965m$$

However, the total settlement for stage 2, involves the settlement due to stage 1 construction continuing in the background, whilst stage 2 settlement also contributes.

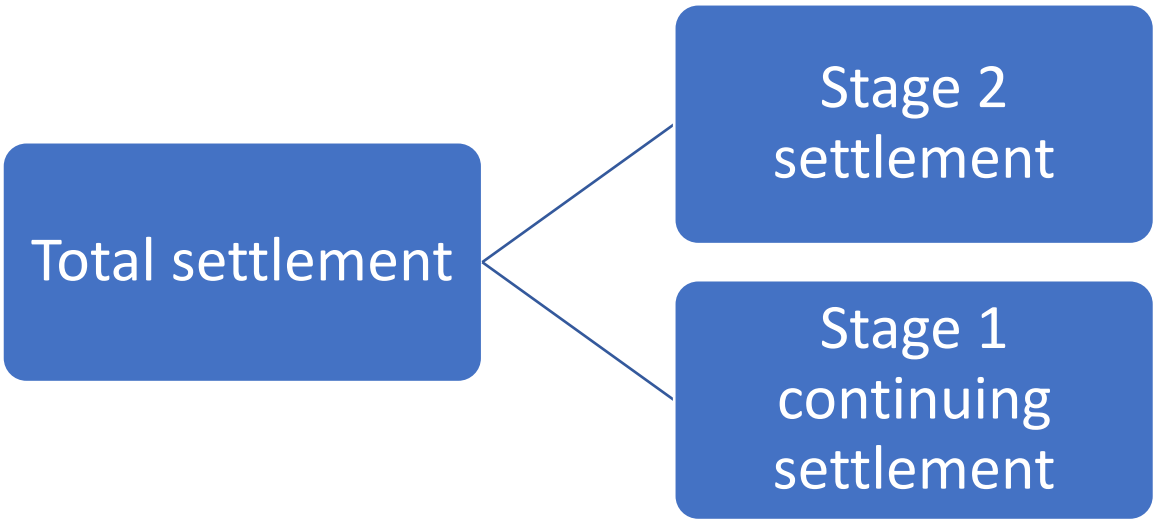

Figure 3.1: Illustration of total settlement for Stage 2

Stage 2 consolidation was optimised at: $U2 = 42\%$, with the updated $H_{dr} = 7.72m$, stage 2 time=11 weeks. Therefore, the underlying stage 1 consolidation process has been in operation for t1+t2=26+11=37 weeks. When t=37 weeks U1=81.4% consolidation. Therefore, S1 is now: $S1 = S1(\max) \times \mathrm{U1} = 2.402 \times 0.814 = 1.955m$, whilst $S2 = 0.42 \times 0.965 = 0.4053m$. As a result, the end of stage 2 construction, the overall settlement is $S = 0.4053 + 1.95 = 2.36m$.

At this point in the construction the overall consolidation is: $U = \frac{2.36}{3.74} = 63.1\%$.

Increase in soil shear strength is: $(\Delta C_u)_2 = 0.25 \times U_2 \times (\Delta\sigma)_2 = 0.25 \times 0.42 \times 54.72 = 5.75kPa$

Therefore, the updated $C_u = 33.84 + 5.75 = 39.59kPa$

As a result, the new $FS = \frac{5.14 \times 39.59}{133.8} = 1.52$>1.3

Stage 3

With the updated shear strength of the soil, and updated factor of safety, more surcharge soil can be added.

Resetting the FoS back to 1.3:

$$\Delta\sigma = \frac{N_c Cu}{FS} = \frac{5.14 \times 39.59}{1.3} = 156.5kPa$$

Therefore, the surcharge added in stage 3 is: $156.5 - 133.8 = 22.72kPa$

Updating the vertical effective stress: $(\sigma_o')_3 = (\sigma_o')_2 + (U)_2 \times (\Delta\sigma')_2 = 90.6 + 0.42 \times 79.08 = 113.6kPa$

The new $H = 9.4 - 2.36 = 7.04m$, therefore $(H_{dr})_3 = 7.04m$.

The void ratio will now change in addition. $\Delta e = \frac{\Delta H}{H_O}(1 + e_O) = \frac{(7.72-7.04)}{7.72}(1 + 0.478) = 0.1302$

Therefore, the new void ratio is: $(e_O)_3 = 0.478 - 0.130 = 0.348$

The additional settlement which can be achieved by adding the stage 3 surcharge is as follows (this is assuming U3=100%).

$$S_3 = \frac{0.9 \times 7.04}{(1 + 0.348)} \times log_{10}\left(\frac{113.6 + 22.72}{113.6}\right) = 0.372m$$

However, the total settlement for stage 3, involves the settlement due to stage 1 and 2 constructions continuing in the background, whilst stage 3 settlement also contributes.

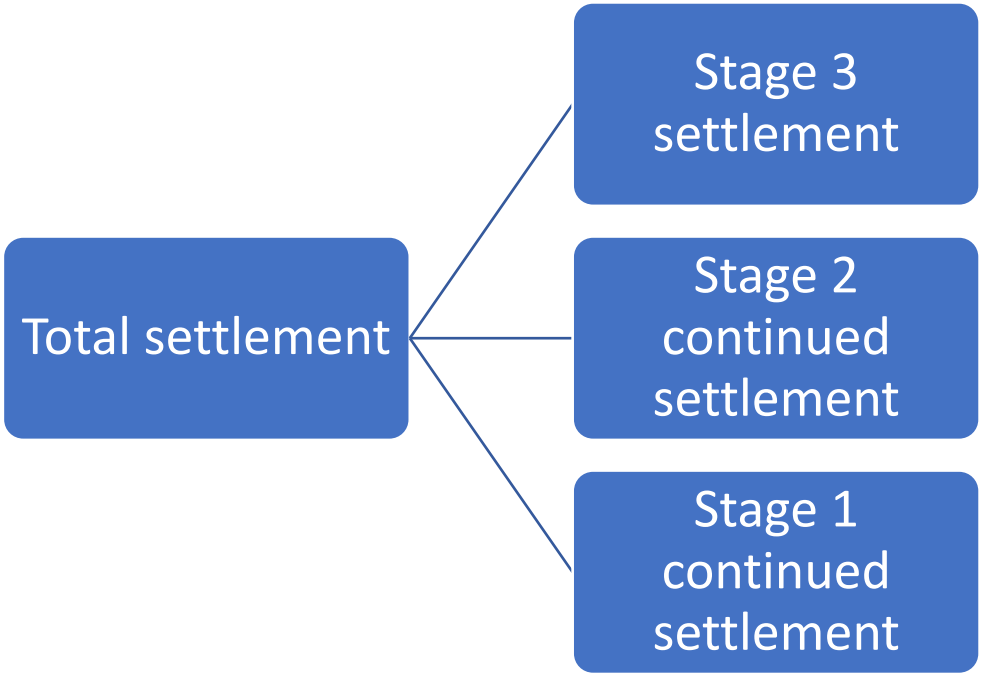

Figure 3.2: Illustration of total settlement for Stage 3

Stage 3 consolidation was optimised at: $U3 = 55\%$, with the updated $H_{dr} = 7.04m$, stage 3 time=16 weeks. Therefore, the underlying stage 1 consolidation process has been in operation for t1+t2+t3=26+11+16=53 weeks. When t=53 weeks U1=90.9% consolidation. Therefore, S1 is now: $S1 = S1(\max) \times \mathrm{U1} = 2.402 \times 0.909 = 2.18m$. Additionally, the underlying stage 2 consolidation process has been in operation for t2+t3=11+16=27 weeks. When t=27 weeks U2=71.3%. Therefore, S2 is now: $S2(\max) \times U2 = 0.964 \times 0.713 = 0.687m$. With $S3 = 0.55 \times 0.372 = 0.2046m$. As a result, the end of stage 3 construction, the overall settlement is $S = 2.18 + 0.687 + 1.95 = 3.07m$.

At this point in the construction the overall consolidation is: $U = \frac{3.07}{3.74} = 81.9\%$.

Increase in soil shear strength is: $(\Delta C_u)_3 = 0.25 \times U_3 \times (\Delta\sigma)_3 = 0.25 \times 0.55 \times 22.72 = 3.124kPa$

Therefore, the updated $C_u = 39.59 + 3.124 = 42.714kPa$

As a result, the new $FS = \frac{5.14 \times 42.714}{156.51} = 1.4$>1.3

Stage 4

With the updated shear strength of the soil, and updated factor of safety, more surcharge soil can be added.

Resetting the FoS back to 1.3:

$$\Delta\sigma = \frac{N_c Cu}{FS} = \frac{5.14 \times 41.714}{1.3} = 168.9kPa$$

Therefore, the surcharge added in stage 4 is: $168.9 - 156.5 = 12.4kPa$

Updating the vertical effective stress: $(\sigma_o')_4 = (\sigma_o')_3 + (U)_3 \times (\Delta\sigma')_3 = 113.6 + 0.55 \times 22.72 = 126.1kPa$

The new $H = 9.4 - 3.07 = 6.33m$, therefore $(H_{dr})_4 = 6.33m$.

The void ratio will now change in addition. $\Delta e = \frac{\Delta H}{H_O}(1 + e_O) = \frac{(7.04-6.33)}{7.04}(1 + 0.348) = 0.136$

Therefore, the new void ratio is: $(e_O)_4 = 0.348 - 0.136 = 0.211$

The additional settlement which can be achieved by adding the stage 4 surcharge is as follows (this is assuming U4=100%).

$$S_4 = \frac{0.9 \times 6.33}{(1 + 0.211)} \times log_{10}\left(\frac{126.1 + 12.4}{126.1}\right) = 0.192m$$

However, the total settlement for stage 4, involves the settlement due to stage 1, 2 and 3 constructions continuing in the background, whilst stage 4 settlement also contributes.

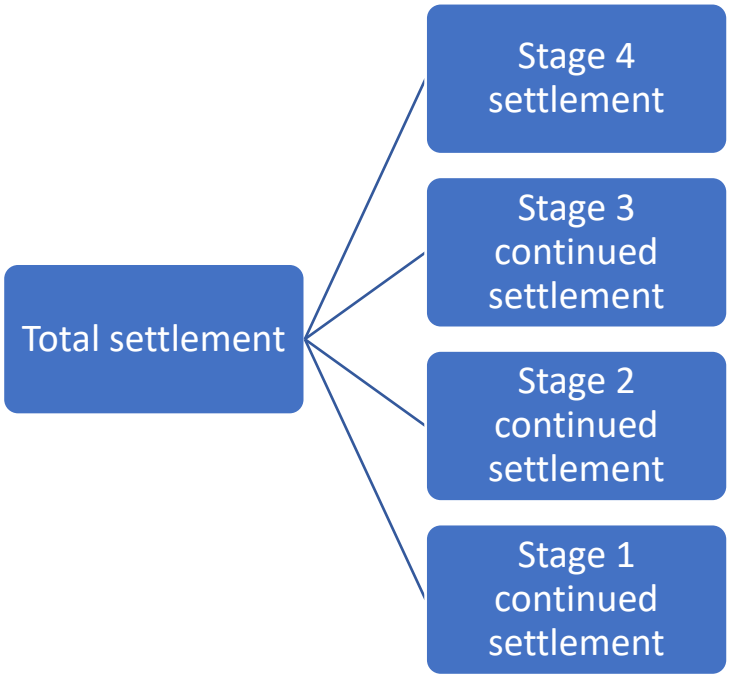

Figure 3.3: Illustration of total settlement for Stage 4

Stage 4 consolidation was optimised at: $U4 = 38\%$, with the updated $H_{dr} = 6.33m$, stage 4 time=9 weeks. Therefore, the underlying stage 1 consolidation process has been in operation for t1+t2+t3+t4=26+11+16+9=62weeks. When t=62 weeks U1=93.9% consolidation. Therefore, S1 is now: $S1 = S1(\max) \times \mathrm{U1} = 2.402 \times 0.939 = 2.26m$. Additionally, the underlying stage 2 consolidation process has been in operation for t2+t3+t4=11+16+9=36 weeks. When t=36 weeks U2=80.8%. Therefore, S2 is now: $S2(\max) \times U2 = 0.964 \times 0.808 = 0.7789m$. Additionally, the underlying stage 3 consolidation process has been in operation for t3+t4=16+9=25 weeks. When t=25 weeks, U3=68.9%. Therefore, S3 is now: $S3(\max) \times U3 = 0.372 \times 0.689 = 0.256m$ With

$S4 = 0.38 \times 0.191 = 0.0726m$. As a result, the end of stage 4 construction, the overall settlement is $S = 2.26 + 0.779 + 0.256 + 0.0726 = 3.37m$.

At this point in the construction the overall consolidation is: $U = \frac{3.37}{3.74} = 90.0\%$.

Height checks at the start of each stage (must be <5.6m above ground level):

Table 2: Check for embankment height above ground level at start of each stage

Start of stage	Embankment height above ground level (m)
1	3.99
2	5.08
3	5.54
4	5.45

4. Height Of Embankment At Each Stage Of Construction

Table 3: Embankment height above ground level at start of each stage

Start of stage	Embankment height above ground level (m)
1	3.99
2	5.08
3	5.54
4	5.45

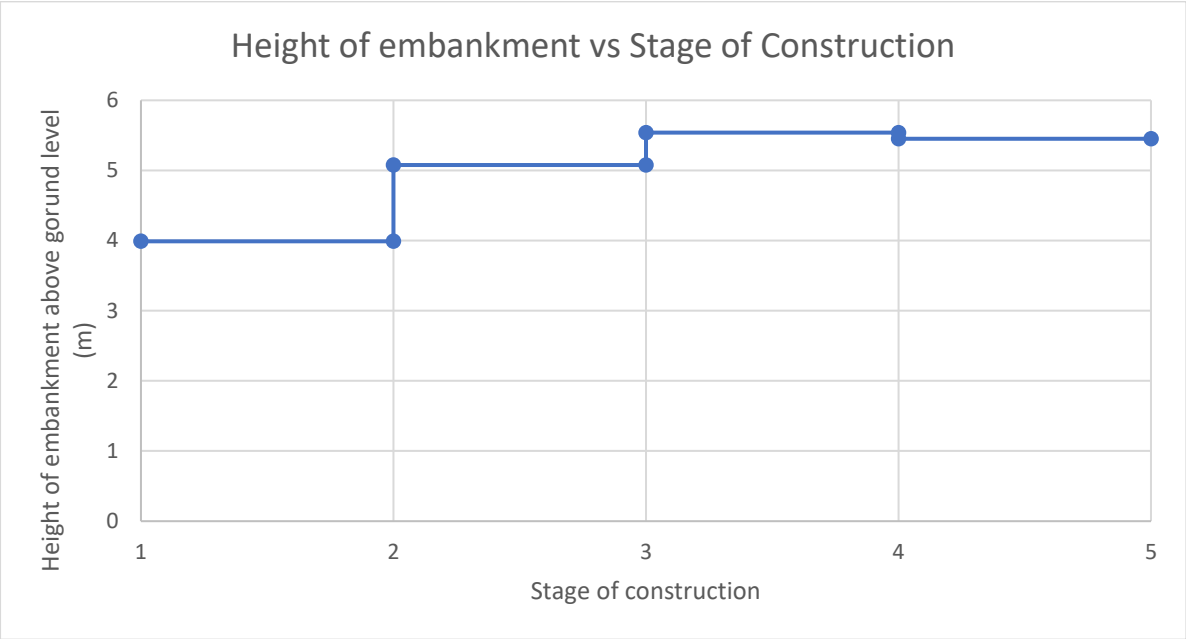

Figure 4.1: Height of embankment at each stage of construction

5. Total Primary Consolidation Settlement Associated With Each Stage Of Construction

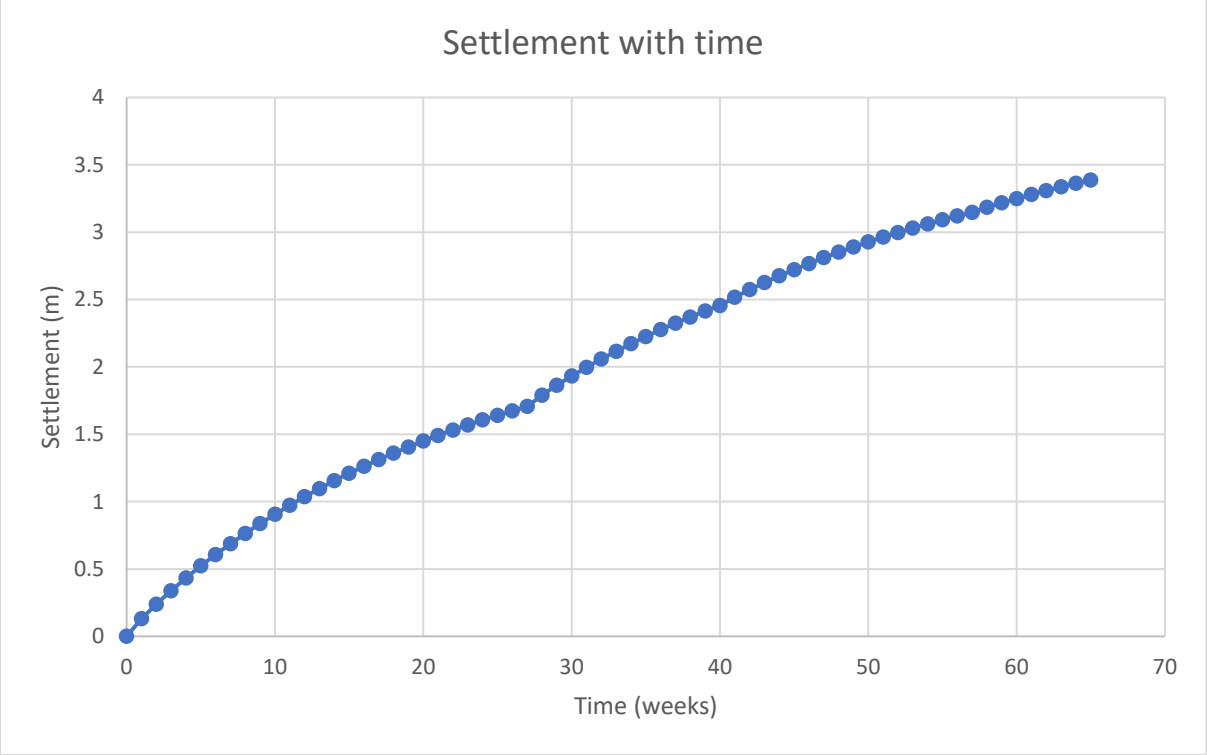

Figure 5.1: Total primary consolidation settlement associated with each stage of construction

Table 4: Total settlement at start of construction and end of construction for each stage

Stage	Start of Construction (m)	End of Construction (m)
1	0	1.673
2	1.673	2.414
3	2.414	3.120
4	3.120	3.387

6. Time Required for 90% Completion Of Primary Consolidation

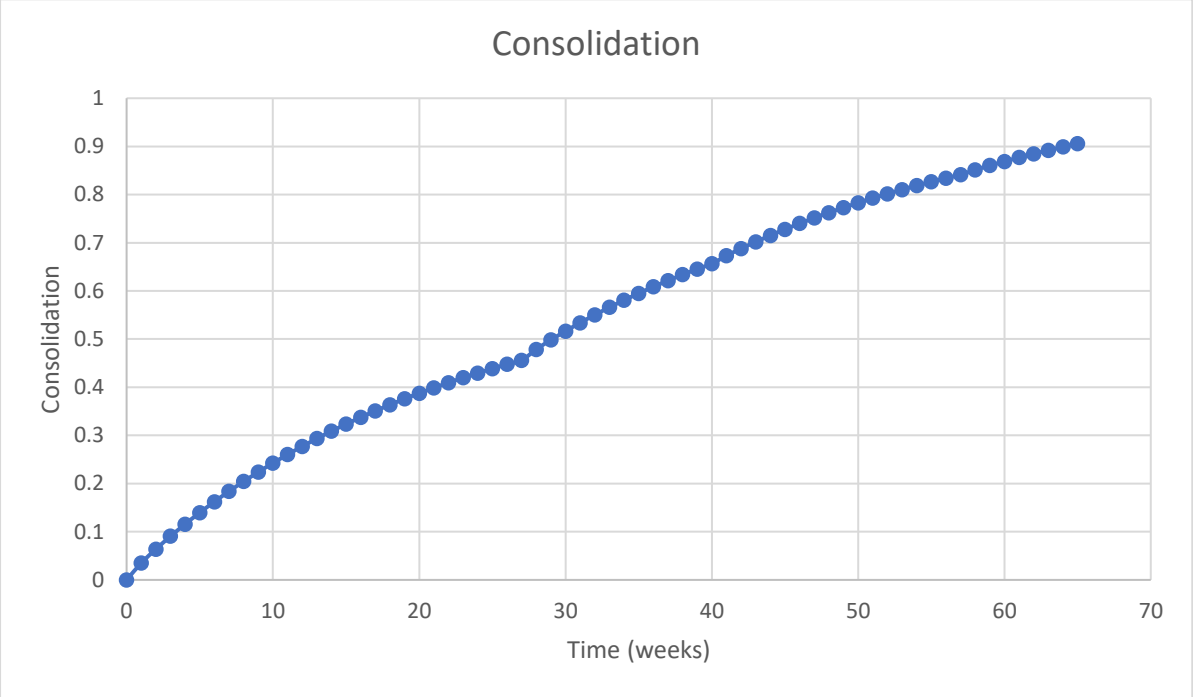

Figure 6.1: Time required for 90% completion of the total primary consolidation

From the calculations in Section 2 And from Figure 6, the 90% completion of primary consolidation is achieved within 65 weeks.

7. Incremental Gain of Strength Per Stage

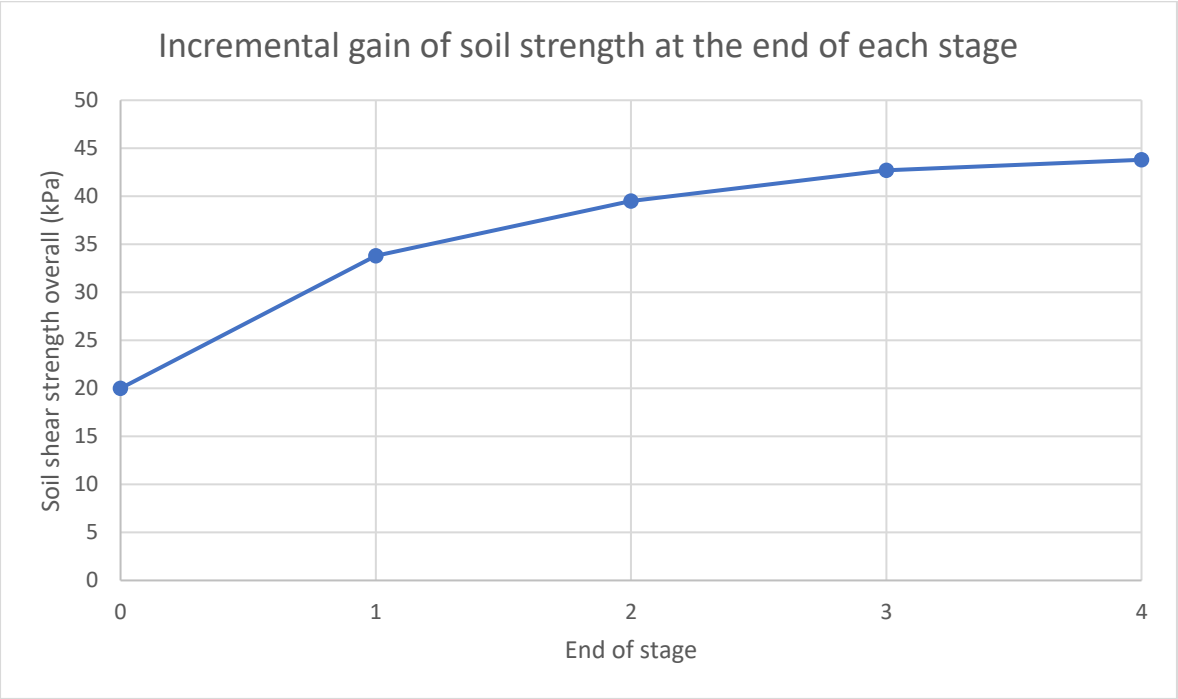

Figure 7.1: Incremental strength gain with each stage

8. Diagram Of Variation Of Backfill Height With Time

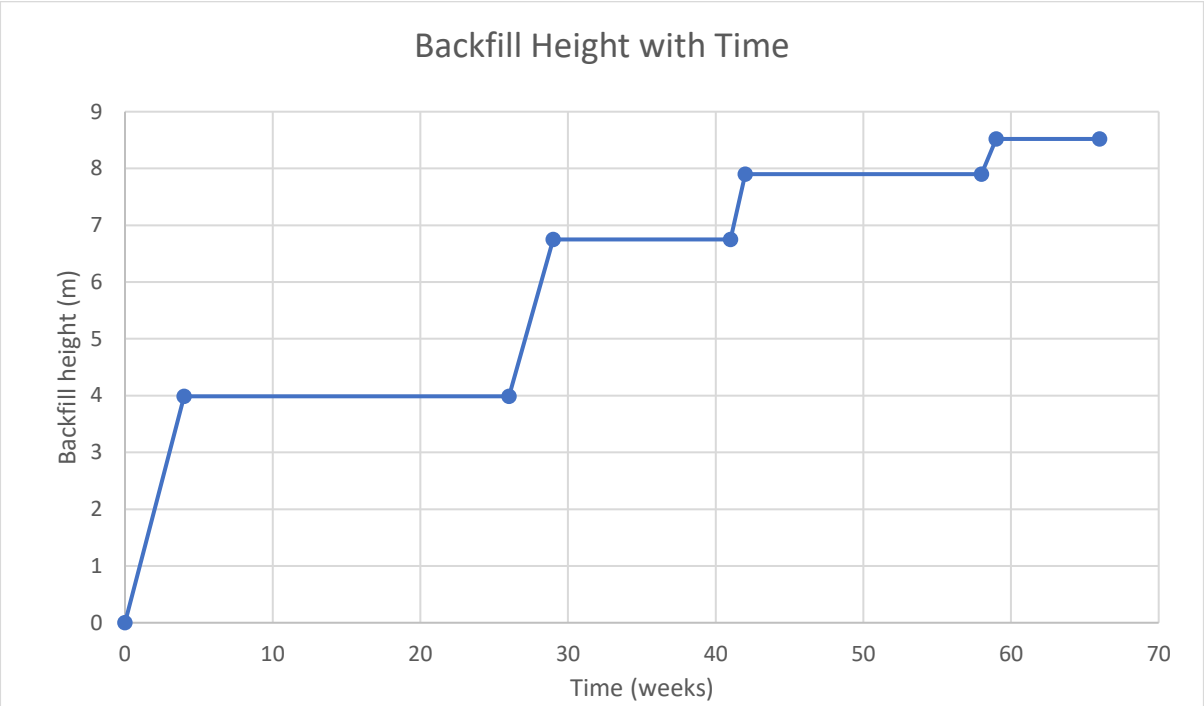

Figure 8.1: Backfill height with time

Table 5: Backfill height at each stage of construction

Stage of Construction	Backfill Height (m)
1	3.99
2	6.75
3	7.90
4	8.52

9. Diagram Of Variation Of Primary Consolidation with Time

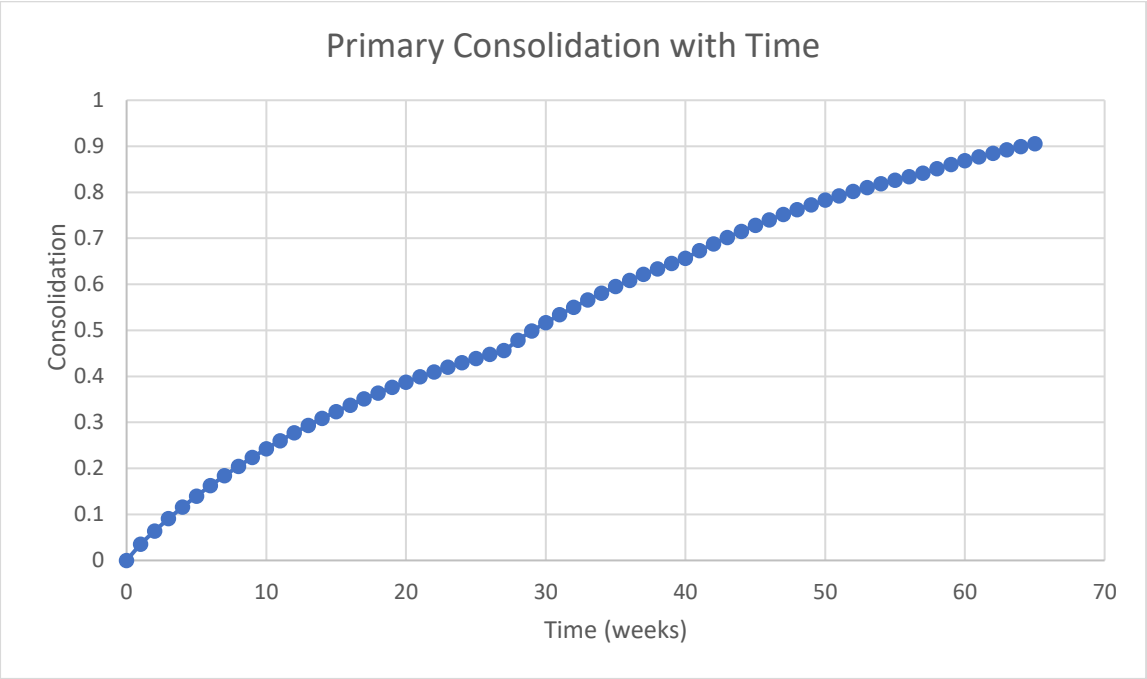

Figure 2: Variation of primary consolidation with time

10. Conclusion

The calculation showed that after several trials, the construction still cannot complete within 12 months to reach 90% consolidation.

One way to decrease the time required to achieve the minimum consolidation would be to make the spacing between the prefabricated vertical drains smaller. Although this would increase the client's cost, requiring more drains for the given embankment, it could reduce to the construction time to within the desired 12month target.

Furthermore, arranging the PVDs in the triangular arrangement is generally preferred, due to the distance between drains will decrease, increasing the rate of consolidation.

Additionally, a surcharge soil could be proposed with a greater unit weight then $19.8\,{}^{kN}/_{m^3}$.

After **65 weeks of construction, the 90% consolidation is achieved**. The surcharge of the embankment will be released, and the consolidation process will be ended.

11. Appendices and Additional Information

These following charts are specific to their individual stages and does NOT represent the overall consolidation.