14.330 SOIL MECHANICS
Assignment #6: Consolidation Settlement.

PROBLEM #1:
- Boring B-1 and Soil Unit Weight Summary (see Assignment Handout).
- 5 ft of fill (SP or SM) to the top of the site with a unit weight of 115 pcf.
- 1D Consolidation Test Results (see Assignment Handout).

REQUIRED:
Calculate the total consolidation settlement in the CL layers due to the addition of the 5 ft of fill.

SOLUTION:
Determine in-situ effective stresses with depth. Only need to calculate to 2\textsuperscript{nd} CL Layer. See Figure A.

![Figure A. Total, Effective, and Pore Water Pressures with Depth.](image-url)
Determine $\Delta \sigma$ due to Planned Fill:

$$\Delta \sigma = (\text{Height of Planned Fill})(\gamma_{\text{fill}}) = (5 \text{ ft})(115 \text{pcf}) = 575 \text{ psf}.$$  

Calculate Change in Void Ratio ($\Delta e$) or Vertical Strain ($\varepsilon_v$) due to Planned Fill:

For 1\textsuperscript{st} CL layer: $\sigma'_{vo}$ @ middle of layer = 1,165 psf (see Figure A). $\Delta \sigma = 575$ psf. $\sigma'_{vl} = 1740$ psf. See Figure B for $\Delta e$ determination.

For 2\textsuperscript{nd} CL layer: $\sigma'_{vo}$ @ middle of layer = 2240 psf (see Figure A). $\Delta \sigma = 575$ psf. $\sigma'_{vl} = 2,815$ psf. See Figure B for $\varepsilon_v$ determination.

Settlement due to Primary Consolidation = $S_p = H \varepsilon_v = H(\Delta e/1+e_o)$

Determine $\Delta e$ and $\varepsilon_v$ from Figure B.

For 1\textsuperscript{st} CL Layer: $S_p = H(\Delta e/(1+e_o)) = 15\text{ft}(0.013/(1+0.64)) = 0.119\text{ft} = 1.43$ inches

For 2\textsuperscript{nd} CL Layer: $S_p = H(\varepsilon_v) = 15\text{ft}(0.0063) = 0.095\text{ft} = 1.13$ inches

$S_{p,\text{total}} = S_{p,\text{Layer1}} + S_{p,\text{Layer2}} = 1.43 \text{ inches} + 1.13 \text{ inches} = 2.56 \text{ inches} = 2 \frac{3}{4} \text{ inches}$ (round up)

$S_{p,\text{total}} = 2\frac{3}{4} \text{ inches}$

PROBLEM #2:

**GIVEN:**

- Footings shown in Figure 3. Working loads of 243 kips for the columns and 12 kips per linear foot for the wall loads.
- Total settlements due to primary consolidation cannot be more than 1 inch, and differential settlement (i.e. the settlement difference between the column and wall footings) cannot be more than ½ inch.

![Figure 3. Planned Shallow Foundation Dimensions for 14.330 Project Site #2 (NTS).](image)
Figure B. $\Delta e$ and $\varepsilon_v$ Determinations from 1D Consolidation Test Data.
PROBLEM 2 (continued)

REQUIRED:
- Calculate the consolidation settlement for these proposed footings.
- Evaluate if the settlement criteria are met or exceeded.

SOLUTION:
Assume that consolidation from 5 ft of fill has occurred. Therefore, $\sigma'_v = \sigma'_f$ from Problem #1.

The new soil profile and total stress, pore pressure, and effective stress calculations are shown in Figure C.

Determine $\Delta\sigma$ due to footings. The 2:1 Method is used in this solution for the column footing and Boussinesq is used for the strip footing. This is done to illustrate two different methods of determining changes in stress due to footing loads. You should be consistent (i.e. use one method for both footings) when you are in industry. Note the following:
1. The 2\textsuperscript{nd} CL layer is 31 ft from the bottom of the column footing and 32 ft from the bottom of the strip footing. This is 3.8B and 8B below the column and strip footings, respectively. Therefore, no significant stress in this lower clay layer due to the footings (i.e. $\Delta \sigma$ will be insignificant in this layer due to either footing). Therefore, no significant settlement will occur in the 2\textsuperscript{nd} CL layer due to the column (or strip) footing.

The upper CL layer is divided into three (3) sub layers to calculate settlement. These sub layers in depth from the ground surface are from (1) 15-17 ft, (2) 17-21 ft, and (3) 21-30 ft. The average $\sigma'_{vo}$, $\Delta \sigma$, and $\sigma'_{vf}$ were calculated for these layers (rounded to the nearest 5 psf) for the column footing are presented in Figure C. Table A summaries the calculations for the change in stress due to the column footing.

**Table A. $\Delta \sigma'$ Calculations for the Strip Footing.**

<table>
<thead>
<tr>
<th>Sub Layer</th>
<th>Depth(^1) (ft)</th>
<th>$\Delta \sigma/q^2$</th>
<th>$\Delta \sigma'^3$ (psf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13 (3.25B)</td>
<td>0.19</td>
<td>570</td>
</tr>
<tr>
<td>2</td>
<td>16 (4B)</td>
<td>0.16</td>
<td>480</td>
</tr>
<tr>
<td>3</td>
<td>22.5 (5.6B)</td>
<td>0.12</td>
<td>360</td>
</tr>
</tbody>
</table>

**NOTES:**
1. Depth below strip footing.
2. See Boussinesq Chart in Lecture Notes.
3. Calculated from $q = 3,000$ psf.

Calculate Change in Void Ratio ($\Delta e$) due to column and strip loading:

**For the column footing:**

Layer 1: $\sigma'_{vo}$ @ middle of layer = 1345 psf (see Figure C). $\sigma'_{vf} = 1950$ psf. See Figure E for $\Delta e$ determination.
Layer 2: $\sigma'_{vo}$ @ middle of layer = 1555 psf (see Figure C). $\sigma'_{vf} = 1975$ psf. See Figure E for $\Delta e$ determination.
Layer 3: $\sigma'_{vo}$ @ middle of layer = 1895 psf (see Figure C). $\sigma'_{vf} = 2160$ psf. See Figure E for $\Delta e$ determination.

**For the strip footing:**

Layer 1: $\sigma'_{vo}$ @ middle of layer = 1345 psf (see Figure C). $\sigma'_{vf} = 1915$ psf. See Figure F for $\Delta e$ determination.
Layer 2: $\sigma'_{vo}$ @ middle of layer = 1555 psf (see Figure C). $\sigma'_{vf} = 2035$ psf. See Figure F for $\Delta e$ determination.
Layer 3: $\sigma'_{vo}$ @ middle of layer = 1895 psf (see Figure C). $\sigma'_{vf} = 2255$ psf. See Figure F for $\Delta e$ determination.
Figure E. $\Delta e$ Determinations from 1D Consolidation Test Data (Column Footing).

Figure F. $\Delta e$ Determinations from 1D Consolidation Test Data (Strip Footing).
Settlement due to Primary Consolidation = \( S_p = H(\Delta e/1+e_o) \)

**For the Column Footing:**

**For Layer 1:** \( S_p = H(\Delta e/1+e_o) = 2ft(0.012/(1+0.64)) = 0.015ft \)

**For Layer 2:** \( S_p = H(\Delta e/1+e_o) = 3ft(0.007/(1+0.64)) = 0.013ft \)

**For Layer 3:** \( S_p = H(\Delta e/1+e_o) = 10ft(0.005/(1+0.64)) = 0.030ft \)

\( S_{p,\text{column}} = S_{p,\text{Layer1}} + S_{p,\text{Layer2}} + S_{p,\text{Layer3}} = 0.058ft = 0.7 \text{ inches} = \frac{3}{4} \text{ inch} \)

**For the Strip Footing:**

**For Layer 1:** \( S_p = H(\Delta e/1+e_o) = 2ft(0.012/(1+0.64)) = 0.015ft \)

**For Layer 2:** \( S_p = H(\Delta e/1+e_o) = 3ft(0.008/(1+0.64)) = 0.015ft \)

**For Layer 3:** \( S_p = H(\Delta e/1+e_o) = 10ft(0.008/(1+0.64)) = 0.049ft \)

\( S_{p,\text{strip}} = S_{p,\text{Layer1}} + S_{p,\text{Layer2}} + S_{p,\text{Layer3}} = 0.079ft = 0.95 \text{ inches} = 1 \text{ inch} \)

**Differential Settlement =** \( S_{p,\text{column}} - S_{p,\text{strip}} = \frac{1}{4} \text{ inches}. \)

Therefore, Settlement Criteria are MET (\( S_{p,\text{column}} = 1 \text{ inch}, \text{ differential settlement} < \frac{1}{2} \text{ inch} \)).

**PROBLEM #3:**
What affect (if any) would decreasing the column footing depth have on the consolidation settlement? What affect (if any) would increasing the column footing depth have on the consolidation settlement? Explain you answer using the relevant concepts in sufficient detail that a non-engineer can understand your answer.

**SOLUTION:**
Decreasing Column Footing Depth results in decreased \( \Delta \sigma \) in CL layers, thereby less settlement would occur. **Simplified:** Higher footing, less stress, less settlement.

Increasing Column Footing Depth results in increased \( \Delta \sigma \) in CL layers, thereby more settlement would occur. **Simplified:** Lower footing, increased stress, more settlement.
PROBLEM #4:

GIVEN:
- 1D Consolidation Test data for 2.2 ksf load increment for the upper CL layer (see Assignment Handout).

REQUIRED:
From the provided information, determine the following:

a. The coefficient of consolidation \( c_v \) using both the log time and square root of time methods. The average height of the soil sample in the 1D consolidation test during the 2 ksf load increment was 0.455 inches.

b. The time to 50% and 99% average degree of consolidation using the \( c_v \)'s calculated from Part a.

c. The expected settlement in this clay layer at \( U_{av} = 50\% \) and \( U_{av} = 99\% \). Use the calculated primary consolidation settlement previously calculated if needed.

d. Do you need to calculate the time to end of primary consolidation for the wall footing? Briefly explain your answer.

SOLUTION:

Part a: Determine the coefficient of consolidation \( c_v \) using both the log time and square root of time methods.

See Figures A and B for determination of \( t_{50} \) and \( t_{90} \), respectively.

To find \( c_v \):

\[
c_v = \frac{T_v H^2}{dr} \frac{dr}{t}
\]

Remember, dual drainage of 1D Test sample. Therefore \( H_{dr} = 0.5H = 0.5(0.455 \text{ in}) = 0.2275 \text{ in} = 0.01790 \text{ ft} \). A summary of calculated \( c_v \) values is provided in Table A.
Figure A. Log Time Method (Casagrande) Analysis.

Figure B. Square Root of Time (Taylor) Method Analysis.
Table A. Summary of Coefficient of Consolidation ($c_v$) Calculations.

<table>
<thead>
<tr>
<th>Method</th>
<th>$t_{50}$ (min)</th>
<th>$t_{90}$ (min)</th>
<th>$T_v$ (Table 7.1, Das FGE 2006)</th>
<th>$c_v$ (ft²/min)</th>
<th>$c_v$ (ft²/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log Time</td>
<td>11.5</td>
<td>NA</td>
<td>0.197</td>
<td>$6.16 \times 10^{-6}$</td>
<td>$8.87 \times 10^{-3}$</td>
</tr>
<tr>
<td>Square Root Time</td>
<td>NA</td>
<td>10.9</td>
<td>0.848</td>
<td>$2.80 \times 10^{-6}$</td>
<td>$4.03 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Part b: Determine the time to 50% and 99% average degree of consolidation using the $c_v$’s calculated from #1.

Using the $c_v$ calculated from Part 1 and knowing that $H_{dr}$ of the upper CL layer is 7.5 ft (dual drainage), $t_{50}$ and $t_{99}$ was calculated. The calculations are summarized in Table B.

Table B. Summary of Time to 50% and 99% Average Degree of Consolidation Calculations.

<table>
<thead>
<tr>
<th>Method</th>
<th>$U$ (%)</th>
<th>$T_v$ (Table 7.1, Das FGE 2006)</th>
<th>$c_v$ (ft²/day)</th>
<th>$t$ (days)</th>
<th>$t$ (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log Time</td>
<td>50</td>
<td>0.197</td>
<td>$8.87 \times 10^{-3}$</td>
<td>1250</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>99</td>
<td>1.781</td>
<td></td>
<td>11299</td>
<td>31.0</td>
</tr>
<tr>
<td>Square Root Time</td>
<td>50</td>
<td>0.197</td>
<td>$4.03 \times 10^{-2}$</td>
<td>275</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>99</td>
<td>1.781</td>
<td></td>
<td>2488</td>
<td>6.8</td>
</tr>
</tbody>
</table>

$$t = \frac{H_{dr}^2 T_v}{c_v}$$

Part c: Determine the expected settlement in this clay layer at $U_{av} = 50\%$ and $U_{av} = 99\%$. Use the calculated primary consolidation settlement from Assignment #6 if needed.
\[ U = \frac{S_t}{S_p} \]

Calculate using \( S_p \) from Assignment #6.

**Part d:** Do you need to calculate the time to end of primary consolidation for the wall footing? Briefly explain your answer.

\[ t = \frac{H_d^2 T_v}{c_v} \]

It will take the same amount of time for the wall footing to reach its consolidation settlement as it will the column footing to reach its consolidation settlement. Therefore, there is no need to calculate \( t \) for the wall footing.

**PROBLEM #5:**

**GIVEN:**
- Calculated primary consolidation settlement (\( S_p \)) from column footing is unacceptable.
- You recommend surcharging the site. The additional 6 ft of fill (i.e. the surcharge) will be placed at a lower degree of compaction (i.e. \( \gamma = 115 \text{pcf} \)).
- Calculations from Assignment #6.

**REQUIRED:**
- Calculate how long it will take for a surcharge of an additional 5 ft of the same fill previously used to equal the settlement from the planned column footing.

**SOLUTION:**

**NOTE:** For the surcharge to work, you will need to add additional fill to the site to mimic the planned column footing load. The planned column footing load in Sub Layer 1 of the 1st CL Layer was 550 psf. Therefore, you would need to add ~5ft of soil to the site in addition to the 6 ft of surcharge. That is a LOT of soil.

\[ \sigma'_o = 1400 \text{ psf} \]

Change in Vertical Stress due to Column Footing (\( \Delta \sigma_p \)):

\[ \Delta \sigma_p = 550 \text{ psf @ middle of 1st CL layer}. \text{ This will be conservative.} \]

Change in Vertical Stress due to Surcharge Fill (\( \Delta \sigma_f \)):

\[ \Delta \sigma_f = (H_{fill})(\gamma_{fill}) = (6 \text{ ft})(110 \text{ pcf}) = 660 \text{ psf} \]
Use **Figure 7.27.** Das FGE (2006) to find U to remove surcharge.

\[
\Delta \sigma'_p / \sigma'_o = (550 \text{ psf})/(1400 \text{ psf}) = 0.39
\]

\[
\Delta \sigma'_f / \Delta \sigma'_p = (660 \text{ psf})/(550 \text{ psf}) = 1.2
\]

\[U = 53\%. \text{ Therefore, } T_v = 0.221 \text{ (Table 7.1, Das FGE 2006)}\]

\[T_v = \frac{c_v t_2}{H_{dr}^2}, t_2 = \frac{H_{dr}^2 T_v}{c_v} \quad \text{where } H_{dr} = 7.5 \text{ ft (dual drainage)}\]
Table C. Summary of Time to Remove Surcharge ($t_2$) Calculations.

<table>
<thead>
<tr>
<th>Method</th>
<th>$T_v @ U = 53%$ (Table 7.1, Das FGE 2006)</th>
<th>$c_v$ (ft²/day)</th>
<th>$t_2$ (days)</th>
<th>$t_2$ (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log Time</td>
<td>0.221</td>
<td>9.65 x 10^{-3}</td>
<td>1402</td>
<td>3.8</td>
</tr>
<tr>
<td>Square Root Time</td>
<td>0.221</td>
<td>3.04 x 10^{-2}</td>
<td>309</td>
<td>0.8</td>
</tr>
</tbody>
</table>