Question 1

A temporary anchored pile wall is to be designed to support a vertical cut of 12 meters in normally consolidated silty clay and over-consolidated Ankara clay as shown in Figure 1. Design the anchored pile wall and answer the following questions.

i. Estimate the net resulting horizontal thrust by using Rankine’s Earth Pressure Theory and limit equilibrium method by using Slide software.

ii. Estimate the pile length (i.e.: depth d) to achieve a FS=1.5 against a global rotational failure again by using Slide software.

iii. If 0.6 inch anchorages are to be used with an allowable capacity of approximately 14 tons, estimate the number of anchorage rows to be used with a horizontal spacing of 2.4m.

iv. Now model the problem by using RocScience RS2 software. Use four rows of anchorages located at 2, 5, 8, 11m below the ground surface. Anchorages are decided to be pre-stressed to 20 tons with an inclination of 10 degrees with the horizontal. Complete the excavation in 4 excavation stages: First excavate until 2.5 meter depth...
and then install the anchor at Level 1. Second, third and fourth stages involves the excavation to 5.5, 8.5, 12m depths and the installation of Level 2, 3 and 4 anchorages.

v. Design the anchorages (i.e.: decide about the trumpet size, # of anchor tendons, grout length and free lengths, etc.)
vi. Estimate the factor of safety against tendon tensile failure and pull-out failure of grout-soil bond.

vii. Draw bending moment, axial force and shear diagrams corresponding to each excavation stage.

viii. Design the pile reinforcement against flexural, axial and shear failure. Assume a minimum concrete cover of 7.5cm and concrete class C30.

ix. Estimate the factor of safety against base heave.

x. Discuss if estimated lateral and vertical displacement profiles behind the pile wall is consistent with available literature. How would you improve the system if the displacements estimated are higher than allowable?

**Question 1.1**

*Estimate the net resulting horizontal thrust by using Rankine’s Earth Pressure Theory and limit equilibrium method by using Slide software.*

Calculation using Rankine’s Earth Pressure Theory:

\[
K_u = \frac{1 - \sin \phi'}{1 + \sin \phi'} = \frac{1 - \sin(27)}{1 + \sin(27)} = 0.376
\]

\[
z_0 = 2c' \sqrt{K_u} / K_u \gamma_{wet} = \frac{2 \times 15 \times \sqrt{0.376}}{0.376 \times 18.5} = 2.64m
\]

\[
p_u = 0.376 \times 18.5 \times (12 - 2.64) - 2 \times 15 \times \sqrt{0.376} = 46.71 kN / m^2 \Rightarrow P_x = \frac{46.71 \times (12 - 2.64)}{2} = 218.61 kN / m
\]
Using Slide software, back analysis is made. Janbu Simplified limit equilibrium method is selected and force elevation is selected to be 3m above the base of the soil mass.

According to the back analysis,

\[ P_x = 183.454 \text{kN/m} \]

**Question 1.2**

*Estimate the pile length (i.e.: depth \( d \)) to achieve a \( FS=1.5 \) against a global rotational failure again by using Slide software.*

In order to maintain overall stability of the system for the failure mode shown in Figure 2, soil profile and a pile is modelled in Slide software.
In the software, pile is modelled as an infinite strength material and by Morgenstern & Price limit equilibrium method, slip surfaces are formed under the modelled pile as shown in Figure 3. After incrementing through various “d” depths, it is found out that,

\[ d = 2m \] is sufficient enough to satisfy the F.S=1.5 criteria with a factor of 1.541 as seen in Figure 3.

**Question 1.3**

*If 0.6 inch anchorages are to be used with an allowable capacity of approximately 14 tons, estimate the number of anchorage rows to be used with a horizontal spacing of 2.4m.*

According to Question 1.1, the values calculated using Rankine’s Earth Pressure Theory and Slide software back analysis are 218kN/m and 183kN/m accordingly. With that in mind we can estimate the lateral force exerted by the soil to be around 20 tons per 1 meter.
<table>
<thead>
<tr>
<th>Rankine</th>
<th>Slide</th>
<th>Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>218.61kN/m</td>
<td>183.454kN/m</td>
<td>20ton/m</td>
</tr>
</tbody>
</table>

If the allowable capacity of one anchorage is about 14 tons and the horizontal spacing of these anchorages would be 2.4m then we can make the following approximation to estimate the number of anchorage rows that should be used,

$$20\text{ton/m} \times 2.4\text{m} = 48\text{ton} \rightarrow \text{Required anchorage capacity per meter.}$$

$$\frac{48\text{ton}}{14\text{ton}} = 3.43 \approx \frac{4\text{anchors}}{\text{meter}} \rightarrow \text{Required anchorage rows per meter.}$$

**Question 1.4**

Now model the problem by using RocScience RS2 software. Use four rows of anchorages located at 2, 5, 8, 11m below the ground surface. Anchorages are decided to be pre-stressed to 20 tons with an inclination of 10 degrees with the horizontal. Complete the excavation in 4 excavation stages: First excavate until 2.5meter depth and then install the anchor at Level 1. Second, third and fourth stages involves the excavation to 5.5, 8.5, 12m depths and the installation of Level 2, 3 and 4 anchorages.
In RS2 software, problem is modelled as shown in Figure 4. Pile penetration depth is used as calculated in Question 1.2. The model is calculated in 5 Stages; first stage being the stage without any excavation and other steps being the excavation and anchorage steps. It should be noted that the values seen in Figure 4 are for preliminary design only and could change with the calculations described in the later chapters.

**Question 1.5**

*Design the anchorages (i.e.: decide about the trumpet size, # of anchor tendons, grout length and free lengths, etc.)*

According to BS8081:2015, the minimum factors of safety for the design of a ground anchor that is permanent are:

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When we run the calculation according to the model described in Question 1.4, the axial force diagram (Stage 5) for the ground anchorages looks like the following.

The maximum axial force for this model is 405.432 kN. The maximum axial force is carried out by the topmost anchorage.

In order to design the anchorage with the given factor of safety, the maximum axial force should be multiplied by 2,

\[ P_{\text{design}} = 405.432 \times 2 = 810.864 \text{kN} \]

To use in the design, the following anchor tendon is selected from Turkish steel tendon supplier “Çelik Halat ve Tel Sanayi A.Ş.”,

<table>
<thead>
<tr>
<th>Type</th>
<th>Diameter (mm)</th>
<th>Cross-Section Area (mm²)</th>
<th>Minimum Failure Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>15.24</td>
<td>140</td>
<td>260.7 kN</td>
</tr>
</tbody>
</table>

With the use of this type of anchor tendon, 4 anchor tendons with a total capacity of 1042.8 kN would satisfy the factor of safety requirement.
After designing the tendon number and diameter, anchorage is designed with an outer diameter of 45mm, inner grout tube diameter of 10mm and appropriate spacer gaps as shown in Figure 5. By taking into consideration of outer centralizers to provide a grout cover of 13mm on both sides, the bore-hole diameter is designed as 71mm.

Free length and fixed length of the anchorage is designed to be 10 and 8m accordingly. This design is based upon trial & error using RS2 software and design insights offered in Prof. K.O.Cetin’s Lecture notes.

Ultimately all design parameters are shown in the following table;

<table>
<thead>
<tr>
<th>Trumpet Size</th>
<th># of Tendons</th>
<th>Borehole Diameter</th>
<th>Inner Grout Tube Diameter</th>
<th>Fixed Length</th>
<th>Free Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>45mm</td>
<td>4</td>
<td>71mm</td>
<td>10mm</td>
<td>8m</td>
<td>10m</td>
</tr>
</tbody>
</table>
**Question 1.6**

*Estimate the factor of safety against tendon tensile failure and pull-out failure of grout-soil bond.*

The calculated tensile force acting on one anchorage is 405.432kN and the ultimate tensile capacity of one anchorage is 1042.8. So the following calculation is made,

\[
F.S. = \frac{1042.8 \text{kN}}{405.43 \text{kN}} = 2.57 \geq 2 \rightarrow O.K.
\]

If the tensile force acting on one anchorage is 405.432kN, the fixed length is 8m and the factor of safety against pull-out failure should be 3, then the following calculations can be made,

\[
405.43 \times 3 = 1216.29 \text{kN/m} \rightarrow \text{Applied Tension Force}
\]

\[
\frac{1216.29 \text{kN/m}}{8 \text{m}} = 152.04 \text{kN/m}^2 \rightarrow \text{Required Skin Friction}
\]

*Figure 6*
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According to Figure 7 and Figure 6 expected skin friction is about ≈150kN/m² due to plasticity and stiffness of the normally consolidated clay soil. So we can say that the estimated skin friction satisfies the F.S=3 criteria. On the other hand, one may use post-grouting techniques to further increase the skin friction in order to be more conservative.

Question 1.7

*Draw bending moment, axial force and shear diagrams corresponding to each excavation stage.*
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Question 1.8

Design the pile reinforcement against flexural, axial and shear failure. Assume a minimum concrete cover of 7.5cm and concrete class C30.

For the design of the pile reinforcement against flexural and axial failure the pile is modelled as a cylindrical column and methods described in A. Topçu’s textbook “Reinforced Concrete” (A. Topçu, 2015) and U. Ersoy’s charts (ERSOY, 1980) are used. On the other hand, design against shear failure is modelled by estimating the pile as a beam.

Concrete & reinforcement specifications are:
- Concrete: C30/37 – $f_{cd} = 20$MPa
- Reinforcement: B420C – $f_{yd} = 365.22$MPa

The chart used for the design,

![Figure 8 - Chart 8-62(ERSOY, 1980)](image)

Assignment 5: The Assessment of the Performance of Anchored Pile Walls with RocScience RS2
Flexural & Axial Failure

- Design Moment: \(1.4 \times 838.54 = 1173.956 \text{kNm}\)
- Design Axial Force: \(1.6 \times 200 = 320 \text{kN}\)

Area of Concrete: \(\frac{800^2 \pi}{4} = 502654.8246 \text{mm}^2\)

\[
\frac{d}{h} = \frac{65}{80} = 0.8125 \Rightarrow \text{Chart 8-62 is selected.}
\]

\[
\frac{N_d}{A_f \cdot f_{cd}} = \frac{320000}{502654.8246 \cdot 20} = 0.0318 \quad \frac{M_d}{A_h \cdot h \cdot f_{cd}} = \frac{1173.956 \times 10^6}{502654.8246 \times 800 \times 20} = 0.146
\]

\(\rho m = 0.28 \Rightarrow \text{Read from the Chart 8-62} \quad \rho \times \frac{f_{yd}}{f_{cd}} = \rho \times \frac{365.22}{20} = 0.28 \Rightarrow \rho = 0.0153\)

\(A_s = 0.0153 \times 502654.8246 = 7707.32 \text{mm}^2 \Rightarrow \text{Required reinforcement area}\)

\(18 \phi 24 \Rightarrow A_s = 8143.01 \text{mm}^2 \geq 7707.32 \text{mm}^2 \Rightarrow \text{Checked.}\)

\(0.01 \leq \rho = \frac{8143.01}{502654.8246} = 0.016 \leq 0.04 \Rightarrow \text{Checked}\)

**18 \Phi 24 Reinforcement is selected.**
Shear Failure

- Design Shear Force = 1.0 \times 307.23 = 307.23 kN
- Design Axial Force = 464.62 \times 1.6 = 743.39 kN

Area of Concrete = \frac{800^2 \pi}{4} = 502654.8246 \text{ mm}^2

Max. Shear Force = V_{max} = 0.22 \times f_{cd} \times A_c = 0.22 \times 20 \times 502654.8246 = 2211.681 kN

Critical Shear Force = V_{cr} = 0.65 \times f_{cd} \times A_c \times \left(1 + \frac{(\gamma = -0.3) \times N_{ck}}{A_c} \right) = 414.942 kN

V_d \leq V_{cr} \leq V_{max} \rightarrow \text{Shear demand can single-handedly fulfilled by concrete cross-section only. Therefore only minimum shear reinforcement is required.}
Question 1.9

Estimate the factor of safety against base heave.

In order to estimate the factor of safety against base heave, a simple method of analysing base stability developed by Bjerrum and Eide (Bjerrum and Eide, 1956) is used. For this method chart showed Figure 9 is used as the following;

$$F = \frac{c_u N_{cb}}{(\gamma_m H + q)} = \frac{N_{cb}}{N}$$

Figure 9 - Bearing Capacity Factors for Base Instability Analysis (Bjerrum and Eide, 1956)
If we were to follow up on those formulations to the problem in hand,

Where,

\[ C_u = 100 \text{kPa} \]
\[ \gamma_m = 18.5 \text{kN/m}^3 \]
\[ H = 12 \text{m} \]
\[ H/B = 0 \]
\[ H/L = 0 \]

Then \( N_{cv} \), from Figure 9 would be 5.2. Later, factor of safety could be calculated,

\[
F = \frac{100 \times 5.2}{(18.5 \times 12 + 0)} = 2.34 \geq 1.5
\]
Question 1.10

*Discuss if estimated lateral and vertical displacement profiles behind the pile wall is consistent with available literature. How would you improve the system if the displacements estimated are higher than allowable?*

If the displacements estimated are higher than allowable, the most effective way to improve displacements is to increase the pre-stress value of the anchorages. Additional anchorage installation or increase in pile diameter (which will increase the rigidity of the wall) would improve the displacements.

References


