Anchor Design Report for Excavation Support Structure

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1 Subject

Construction stage for which calculations are performed: Final Excavation

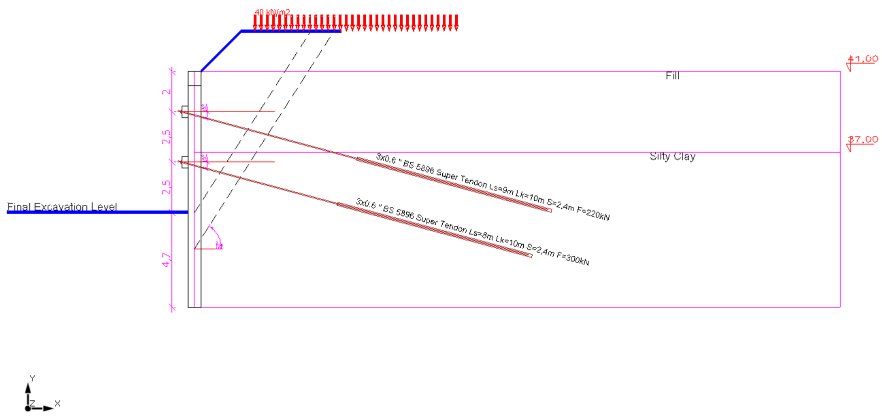

Figure 1: Section of the excavation support structure

2 Ultimate Limit State

Verification of resistance for structural and soil limit states in permanent and temporary situations:

$$E_d \leq R_d \tag{1}$$

E : Action effect

E_d : Design value of the action effect

R : Resistance

R_d : Design value of resistance

$$E_d = \gamma_A E \left\{F_{rep}; X_k/\gamma_M; a_d\right\} \tag{2}$$

γ_A : Partial factor for actions

F_{rep} : Representative values of actions

X_k : Characteristic values of geotechnical parameters

γ_M : Partial factor for soil parameters

a_d : Design values of geometrical data

3 Anchored Systems

In anchored systems, the following failure modes are checked: interface slip between the grout body and soil, interface slip between the tendon and grout body, and tendon tensile failure.

3.1 Bond Resistance at the Grout/Ground Interface

Ultimate load transfer capacity in the anchor bond length:

$$T_f = \pi \cdot D \cdot L_{tb} \cdot \tau_f \tag{3}$$

Characteristic load transfer capacity in the anchor bond length:

$$T_k = \frac{T_f}{\xi} \tag{4}$$

D : Effective diameter of the root zone

L_{tb} : Length of the tendon in the bond zone

τ_f : Ultimate bond stress for ground/grout interface along anchor bond zone

ξ : Safety factor for bond stress at the ground/grout interface

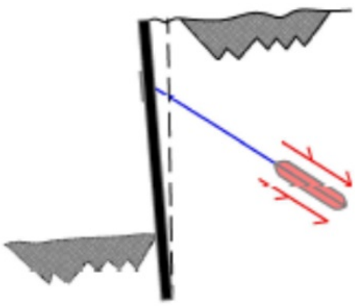

Figure 2: Interface slip failure between grout body and soil

Ultimate bond stress at the grout/ground interface for total stresses:

$$\tau_f = \alpha_a \cdot S_u \tag{5}$$

α_a : Adhesion factor

S_u : Undrained shear strength

Ultimate bond stress at the grout/ground interface for effective stresses:

$$\tau_f = K_1 \cdot \sigma'_v \cdot \tan\phi' \tag{6}$$

K_1 : Earth pressure coefficient for anchors installed by gravity grouting

σ'_v : Vertical effective stress

ϕ' : Internal friction angle

Determination of ultimate bond stress at the grout/ground interface using empirical methods:

$$\tau_f \rightarrow \text{empirical/tables} \tag{7}$$

If the ultimate bond stress is determined using characteristic geotechnical parameters, $\xi = 1$ is used. The ultimate bond stress τ_f can also be determined by anchor tests.

3.2 Tensile Strength of Tendon

Anchor tensile strength:

$$R_t = n \cdot F_u \tag{8}$$

n : Tendon number

F_u : Tensile failure load of a single tendon

$$F_u = A_1 \cdot f_u \tag{9}$$

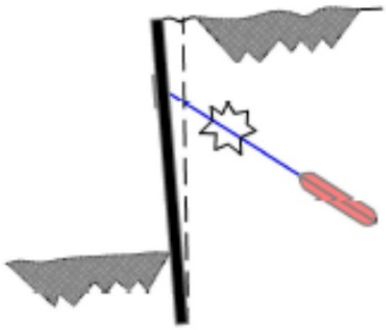

Figure 3: Tensile failure of anchor

f_u : Nominal tensile strength of the tendon,

A_1 : Nominal cross-sectional area of a tendon

$$A_1 = \frac{\pi \cdot {d_1}^2}{4} \tag{10}$$

d_1 : Nominal diameter of a single tendon

3.3 Tendon/Grout Bond Strength

Pull-out resistance of the tendon from the grout:

$$R_c = \pi \cdot d_s \cdot L_{tb} \cdot \tau_c \tag{11}$$

τ_c : Tendon-to-grout bond strength

d_s : Diameter of the anchor bar; for multiple tendons, this is the nominal equivalent combined diameter.

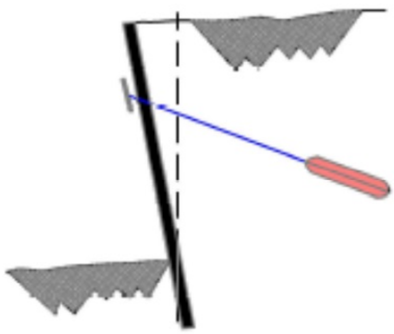

Figure 4: Slip failure at the tendon/grout interface

Tendon-to-grout bond strength is determined according to TS500.

$$C_1 = \frac{1}{4 \cdot C_0} \tag{12}$$

$$f_{ctd} = 0.35 \cdot \sqrt{f_c} \tag{13}$$

$$\tau_c = C_1 \cdot f_{ctd} \tag{14}$$

f_c : Grout compressive strength

f_{ctd} : Tensile strength of grout

C_0 : Experimental coefficient

C_1 : Coefficient applied to grout tensile stress

Tendon-to-grout bond strength is determined according to ACI.

$$\tau_c = 3,3\sqrt{f_c} \rightarrow \tau_c \leq 689kPa \tag{15}$$

4 Anchor Internal Stability

The internal stability of anchored excavation support systems is evaluated through block analyses conducted for all potential failure blocks at each construction stage. For every stage, block analysis is performed for all active anchors. In the block analysis of a verified anchor, the forces from other anchors in the same construction stage are included if they affect the block.

The block is defined by connecting the theoretical bottom point of the wall (A) with the midpoint of the anchor bond length (B), and extending a vertical line from this point to the ground surface (Figure 5).

E_a : Active earth force between points A and D [F/L]

E_{ai} : Active earth force acting on segment BC [F/L]

W_i : Weight of the ABCD block [F/L]

C_i : Cohesive resistance force along the AB slip surface [F/L]

$F_{j,k}$: Anchor forces included in the block analysis other than the verified anchor [F/L]

Q_i : Reaction force on the AB slip surface

F_i : Allowable maximum force of the verified anchor [F/L]

The equilibrium problem is solved by writing vertical and horizontal equilibrium equations for the block.

At the end of the analysis, the allowable maximum force of the verified anchor, F_i, is determined. Equilibrium equations:

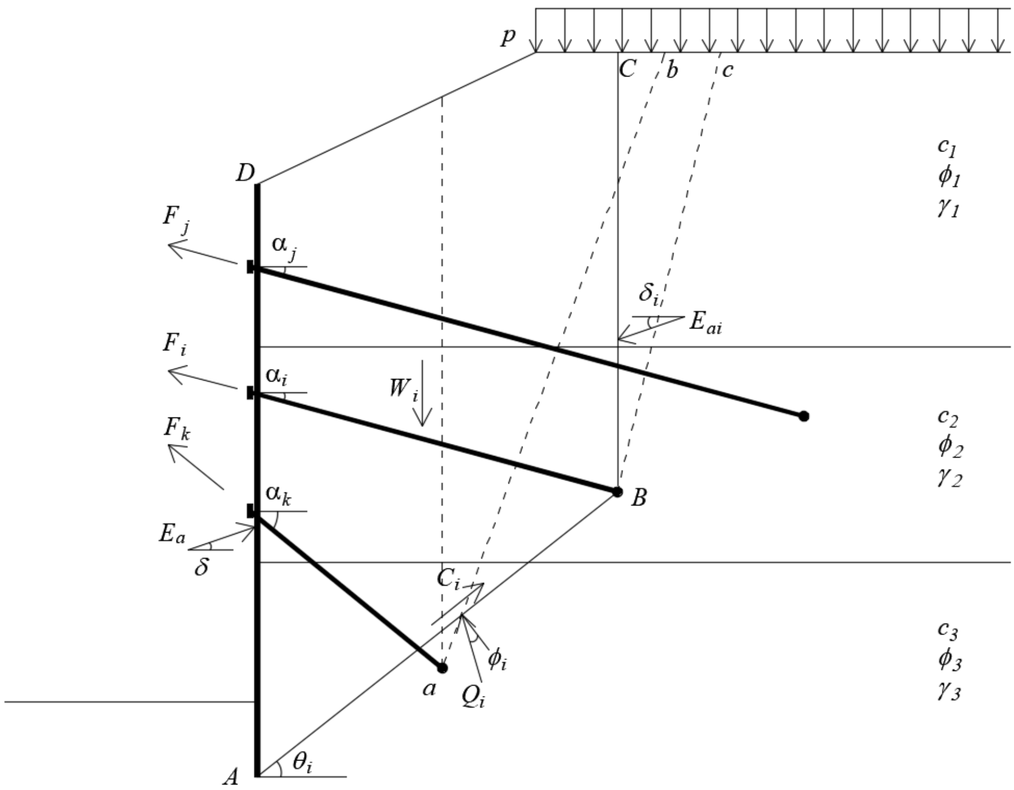

Figure 5: Internal stability analysis

$$\begin{bmatrix} \cos\alpha_i & \cos(90+\phi_i-\theta_i) \\ \sin\alpha_i & \sin(90+\phi_i-\theta_i \end{bmatrix} \begin{bmatrix} F_i \\ Q_i \end{bmatrix} = \begin{bmatrix} E_a \times \cos\delta + C_i \times \cos\theta_i - E_{ai} \times \cos\delta_i - \sum\limits_{j,k..} F_{j,k..} \times \cos\alpha_{j,k..} \\ W_i + E_{ai} \times \sin\delta_i - C_i \times \sin\theta_i - E_a \times \sin\delta - \sum\limits_{j,k..} F_{j,k..} \times \sin\alpha_{j,k..} \end{bmatrix} \tag{16}$$

δ : Average wall/soil friction angle along segment AD

θ_i : Inclination angle of segment AB with respect to the horizontal

δ_i : Weighted average wall/soil friction angle along segment BC

ϕ_i : Average shear strength angle along segment AB

α_i : Inclination angle of the verified anchor with respect to the horizontal

$\alpha_{j,k..}$: Inclination angles of other anchors included in the block analysis, excluding the verified anchor

The factor of safety is calculated as $FS = \frac{F_i}{F}$.

5 Ankraj1 [Kot=39m]

Anchor type: Prestressed anchor with steel strands

$D = 150mm$ $L_{tb} = 10m$

Interface Slip Failure between Grout Body and Soil

The soil zones interacting with the anchor bond length are identified. In each zone, the pullout resistance from the soil is calculated based on drainage conditions. If multiple interaction zones exist, their individual resistances are summed to determine the total pullout resistance of the anchor.

- Interacting 1st Soil Layer: Silty Clay [Drained]

$L_{tbi} = 10m$ $K_1 = 2.4$ $\sigma'_{vi} = 118.68kN/m^2$ $\phi_i = 24°$

The ultimate bond stress was obtained by applying Equation (6).

$$\tau_{fi} = 2.4 \times 118.68 \times \tan 24 = 126.82kN/m^2$$

The ultimate load capacity of the anchor bond length for the active layer was calculated using Equation (3).

$$T_{fi} = \pi \times 0.15 \times 10 \times 126.82 = 597.62kN$$

- Ultimate load transfer capacity in the anchor bond length:

$$T_f = \sum_{1}^{1} T_{fi} = 597.62kN$$

The characteristic load capacity of the anchor bond length was calculated using Equation (4).

$$T_k = \frac{597.62}{1} = 597.62kN$$

- Design Based on Pullout Resistance

Anchor force: $F = 236.3kN$

Partial factor applied to the anchor force caused by actions: $\gamma_A = 1.35$

Partial factor applied to resistances: $\gamma_R = 1.4$

Anchor design force:

$$E_{a;d} = \gamma_A \times F = 1.35 \times 236.3 = 319.01kN$$

Design pullout resistance of the anchor from the ground:

$$R_{a;d} = \frac{T_k}{\gamma_R} = \frac{597.62}{1.4} = 426.87kN$$

Factor of safety:

$$GS_a = \frac{T_f}{F} = \frac{597.62}{236.3} = 2.53$$

$E_{a;d} = 319.01kN \leq R_{a;d} = 426.87kN \rightarrow$ Ultimate load capacity of the anchor bond length is adequate. ✓

Tendon Tensile Failure

$n = 3$ $d_1 = 15.7mm$ $f_u = 1770MPa$

Nominal cross-sectional area of a single tendon for 0.6 " BS5916 Super Tendon:

$$A_1 = 150mm^2$$

Tensile failure force of a single tendon calculated using Equation (9):

$$F_u = 0.00015 \times 1770 = 0.2655MN = 265.5kN$$

Anchor tensile strength determined based on Equation (8):

$$R_t = 3 \times 265.5 = 796.5kN$$

Anchor design tensile strength:

$$R_{t;d} = \frac{R_t}{\gamma_R} = \frac{796.5}{1.4} = 568.93kN$$

Factor of safety:

$$GS_t = \frac{R_t}{F} = \frac{796.5}{236.3} = 3.37$$

$E_{a;d} = 319.01kN \leq R_{t;d} = 568.93kN \rightarrow$ Anchor tensile strength is adequate. ✓

Tendon/Grout Bond Strength

$d_s = 47.1mm$ $f_c = 10MPa$

For ribbed bars $C_0 = 0,24$

Coefficient calculated using Equation (12):

$$C_1 = \frac{1}{4 \times 0.24} = 1.04$$

Concrete tensile strength calculated using Equation (13):

$$f_{ctd} = 0.35 \times \sqrt{10} = 1106.8kN/m^2$$

Tendon-to-grout bond strength calculated using Equation (14):

$$\tau_c = 1.04 \times 1106.8 = 1151.07kN/m^2$$

Tendon-to-grout pullout resistance calculated using Equation (11):

$$R_c = \pi \times 0.047099999999999996 \times 10 \times 1151.07 = 1703.23kN$$

Design tendon-to-grout pullout resistance:

$$R_{c;d} = \frac{R_c}{\gamma_R} = \frac{1703.23}{1.4} = 1216.59kN$$

Factor of safety:

$$GS_c = \frac{R_t}{F} = \frac{1703.23}{236.3} = 7.21$$

$E_{a;d} = 319.01kN \leq R_{c;d} = 1216.59kN \rightarrow$ Design tendon-to-grout pullout resistance is adequate. ✓

Anchor Internal Stability

Depth of point A in Figure 5 below the excavation level $H_o = 0.69m$

$E_a = 307.45kN/m$

$\delta = 15°$

$W_i = 2070.74kN/m$

$\theta_i = 8.67°$

$E_{ai} = 191.58kN/m$

$\delta_i = 15°$

$C_i = 164.15kN/m$

$\phi_i = 24°$

$\alpha_i = 15°$

Other anchors included in the block analysis: none

Sum of the horizontal components of other anchor forces: $\sum_{j,k..} F_{j,k..} \times \cos \alpha_{j,k..} = 0kN/m$

Sum of the vertical components of other anchor forces: $\sum_{j,k..} F_{j,k..} \times \sin \alpha_{j,k..} = 0kN/m$

Based on Equation (16):

$$\begin{bmatrix} \cos 15 & \cos(90+24-8.67) \\ \sin 15 & \sin(90+24-8.67) \end{bmatrix} \begin{bmatrix} F_i \\ Q_i \end{bmatrix} = \begin{bmatrix} 307.45 \times \cos 15 + 164.15 \times \cos 8.67 - 191.58 \times \cos 15 - 0 \\ 2070.74 + 191.58 \times \sin 15 - 164.15 \times \sin 8.67 - 307.45 \times \sin 15 - 0 \end{bmatrix}$$

$Q_i = 1876.36kN/m$ ve $F_i = 797.3kN/m$ elde edilir.

Anchor effect per unit length: $F = 98.46kN/m$

Factor of safety for internal stability: $GS = \frac{F_i}{F} = \frac{797.3}{98.46} = 8.1$

Allowable design force of the anchor:

$$R_{s;d} = \frac{F_i}{\gamma_R} = \frac{797.3}{1.4} = 569.5kN/m$$

Design force per unit length:

$$E_{s;d} = \gamma_A \times F = 1.35 \times 98.46 = 132.92kN/m$$

$E_{s;d} = 132.92kN/m \leq R_{s;d} = 569.5kN/m \rightarrow$ internal stability of the verified anchor is adequate. ✓

6 Anchor2 [Kot=36.5m]

Anchor type: Prestressed anchor with steel strands

$D = 150mm$ $L_{tb} = 10m$

Interface Slip Failure between Grout Body and Soil

The soil zones interacting with the anchor bond length are identified. In each zone, the pullout resistance from the soil is calculated based on drainage conditions. If multiple interaction zones exist, their individual resistances are summed to determine the total pullout resistance of the anchor.

- Interacting 1st Soil Layer: Silty Clay [Drained]

$L_{tbi} = 10m$ $K_1 = 2.4$ $\sigma'_{vi} = 161.57kN/m^2$ $\phi_i = 24°$

The ultimate bond stress was obtained by applying Equation (6).

$$\tau_{fi} = 2.4 \times 161.57 \times \tan 24 = 172.65kN/m^2$$

The ultimate load capacity of the anchor bond length for the active layer was calculated using Equation (3).

$$T_{fi} = \pi \times 0.15 \times 10 \times 172.65 = 813.58kN$$

- Ultimate load transfer capacity in the anchor bond length:

$$T_f = \sum_{1}^{1} T_{fi} = 813.58kN$$

The characteristic load capacity of the anchor bond length was calculated using Equation (4).

$$T_k = \frac{813.58}{1} = 813.58kN$$

- Design Based on Pullout Resistance

Anchor force: $F = 339.76kN$

Partial factor applied to the anchor force caused by actions: $\gamma_A = 1.35$

Partial factor applied to resistances: $\gamma_R = 1.4$

Anchor design force:

$$E_{a;d} = \gamma_A \times F = 1.35 \times 339.76 = 458.67kN$$

Design pullout resistance of the anchor from the ground:

$$R_{a;d} = \frac{T_k}{\gamma_R} = \frac{813.58}{1.4} = 581.13kN$$

Factor of safety:

$$GS_a = \frac{T_f}{F} = \frac{813.58}{339.76} = 2.39$$

$E_{a;d} = 458.67kN \leq R_{a;d} = 581.13kN \rightarrow$ Ultimate load capacity of the anchor bond length is adequate. ✓

Tendon Tensile Failure

$n = 3$ $d_1 = 15.7mm$ $f_u = 1770MPa$

Nominal cross-sectional area of a single tendon for 0.6 " BS5916 Super Tendon:

$$A_1 = 150mm^2$$

Tensile failure force of a single tendon calculated using Equation (9):

$$F_u = 0.00015 \times 1770 = 0.2655MN = 265.5kN$$

Anchor tensile strength determined based on Equation (8):

$$R_t = 3 \times 265.5 = 796.5kN$$

Anchor design tensile strength:

$$R_{t;d} = \frac{R_t}{\gamma_R} = \frac{796.5}{1.4} = 568.93kN$$

Factor of safety:

$$GS_t = \frac{R_t}{F} = \frac{796.5}{339.76} = 2.34$$

$E_{a;d} = 458.67kN \leq R_{t;d} = 568.93kN \rightarrow$ Anchor tensile strength is adequate. ✓

Tendon/Grout Bond Strength

$d_s = 47.1mm\ f_c = 10MPa$

For ribbed bars $C_0 = 0,24$

Coefficient calculated using Equation (12):

$$C_1 = \frac{1}{4 \times 0.24} = 1.04$$

Concrete tensile strength calculated using Equation (13):

$$f_{ctd} = 0.35 \times \sqrt{10} = 1106.8kN/m^2$$

Tendon-to-grout bond strength calculated using Equation (14):

$$\tau_c = 1.04 \times 1106.8 = 1151.07kN/m^2$$

Tendon-to-grout pullout resistance calculated using Equation (11):

$$R_c = \pi \times 0.047099999999999996 \times 10 \times 1151.07 = 1703.23kN$$

Design tendon-to-grout pullout resistance:

$$R_{c;d} = \frac{R_c}{\gamma_R} = \frac{1703.23}{1.4} = 1216.59kN$$

Factor of safety:

$$GS_c = \frac{R_t}{F} = \frac{1703.23}{339.76} = 5.01$$

$E_{a;d} = 458.67kN \leq R_{c;d} = 1216.59kN \rightarrow$ Design tendon-to-grout pullout resistance is adequate. ✓

Anchor Internal Stability

Depth of point A in Figure 5 below the excavation level $H_o = 0.69m$

$E_a = 307.45kN/m$

$\delta = 15°$

$W_i = 2173.54kN/m$

$\theta_i = -0.81°$

$E_{ai} = 318.62kN/m$

$\delta_i = 15°$

$C_i = 150.7kN/m$

$\phi_i = 24°$

$\alpha_i = 15°$

Other anchors included in the block analysis: 1st

Sum of the horizontal components of other anchor forces: $\sum_{j,k..} F_{j,k..} \times \cos \alpha_{j,k..} = 95.11 kN/m$

Sum of the vertical components of other anchor forces: $\sum_{j,k..} F_{j,k..} \times \sin \alpha_{j,k..} = 25.48 kN/m$

Based on Equation (16):

$$\begin{bmatrix} \cos 15 & \cos(90+24--0.81) \\ \sin 15 & \sin(90+24--0.81) \end{bmatrix} \begin{bmatrix} F_i \\ Q_i \end{bmatrix} = \begin{bmatrix} 307.45 \times \cos 15 + 150.7 \times \cos -0.81 - 318.62 \times \cos 15 - 95.11 \\ 2173.54 + 318.62 \times \sin 15 - 150.7 \times \sin -0.81 - 307.45 \times \sin 15 - 25.48 \end{bmatrix}$$

$Q_i = 2098.84 kN/m$ ve $F_i = 958.22 kN/m$ elde edilir.

Anchor effect per unit length: $F = 141.57 kN/m$

Factor of safety for internal stability: $GS = \frac{F_i}{F} = \frac{958.22}{141.57} = 6.77$

Allowable design force of the anchor:

$$R_{s;d} = \frac{F_i}{\gamma_R} = \frac{958.22}{1.4} = 684.45 kN/m$$

Design force per unit length:

$$E_{s;d} = \gamma_A \times F = 1.35 \times 141.57 = 191.11 kN/m$$

$E_{s;d} = 191.11 kN/m \leq R_{s;d} = 684.45 kN/m \rightarrow$ internal stability of the verified anchor is adequate. ✓

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