

Geotechnical Report on Foundation Bearing Capacity

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1 Subject

This report presents the bearing capacity calculations for the structure located in parcel 112, block 47A, map sheet PL-874233. 6 foundation(s) have been analyzed for bearing capacity. Firstly, the shallow foundation bearing capacity is calculated. If a rigid inclusion (column) is defined beneath the foundation, both single and group rigid column bearing capacities are also evaluated. For foundations with rigid inclusions, the shallow foundation and rigid column group bearing capacities are combined to determine the total bearing capacity. The report also includes theoretical background, governing equations, and detailed calculations related to bearing capacity analysis.

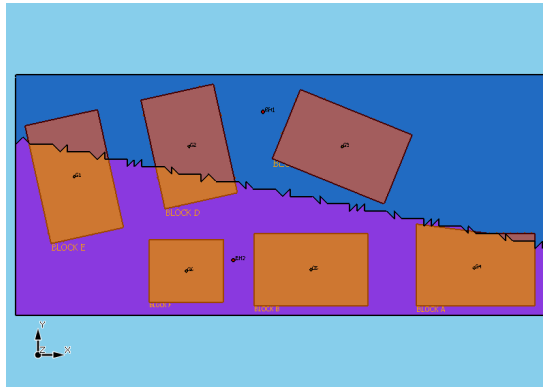


Figure 1: Foundation plan

2 Bearing Capacity of Shallow Foundation

The bearing capacity of shallow foundations was calculated using the methods of Terzaghi, Meyerhof, and Vesic. The geotechnical parameters used in the bearing capacity equations were determined by calculating the weighted average of the mechanical and physical properties of the soil layers extending from the top of the foundation to a depth of B below the foundation base.

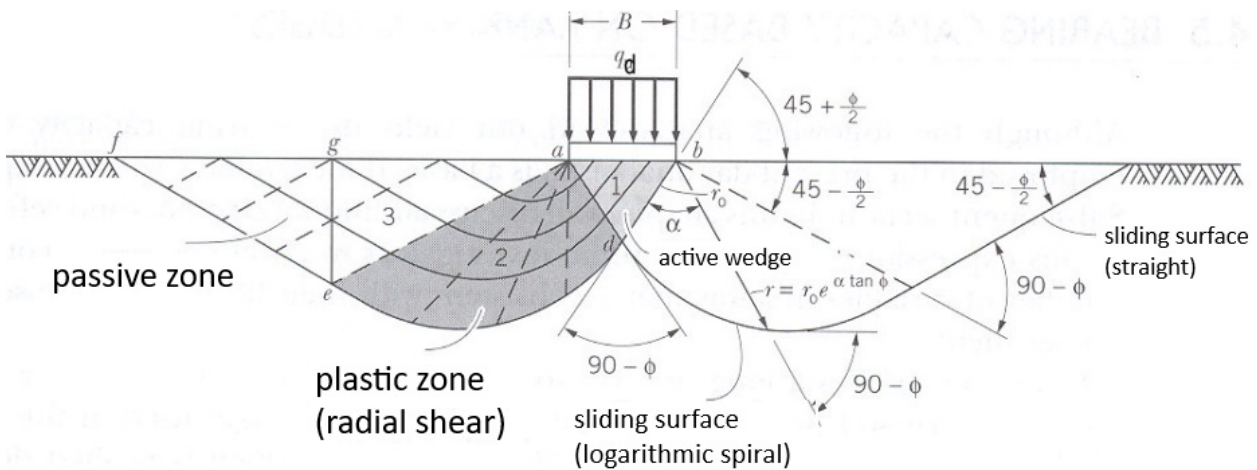


Figure 2: Prandtl model of bearing capacity failure

The ultimate bearing capacity of the foundation can be calculated using the Prandtl model shown in Figure 2. In this case, due to the shearing action of wedge No. 1—remaining in elastic equilibrium—against region No. 2, a series of logarithmic spiral-shaped slip surfaces with variable radii of $r_0 e^{\alpha \tan \phi}$ are formed. Region No. 3 is the soil wedge that has transitioned into a passive state. Other methods developed by following this approach can be considered as variations of the Prandtl solution.

In addition to the active and passive wedges, Terzaghi introduced three significant modifications, as shown in Figure 3. These are: taking the inclination of wedge No. 1 as ϕ instead of $45 + \phi/2$; considering the foundation base as rough rather than smooth; and assuming that the soil exhibits no shear resistance along the embedment depth D_f , acting instead as an equivalent surcharge load $q = \rho D_f$.

The main concept behind the bearing capacity solutions developed by Terzaghi and others, based on this and other assumptions, can be illustrated using a simplified model as shown in Figure 4. In this model, the ultimate bearing capacity—represented by the load q_d that brings

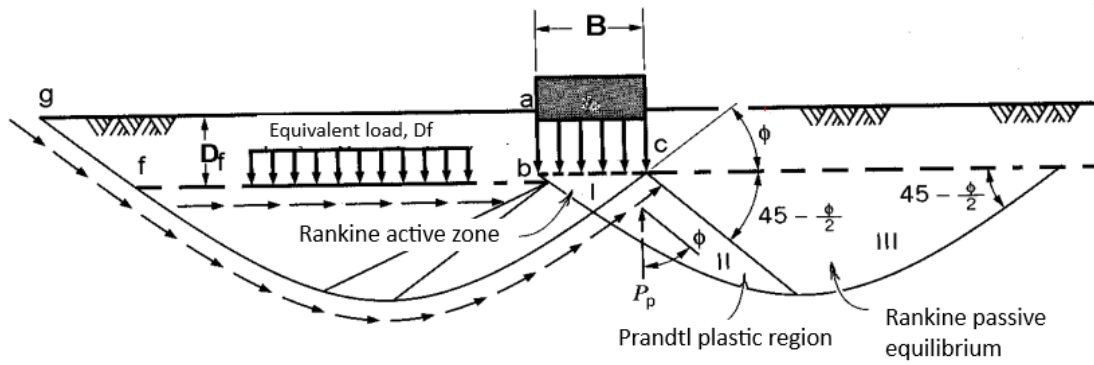


Figure 3: Terzaghi model

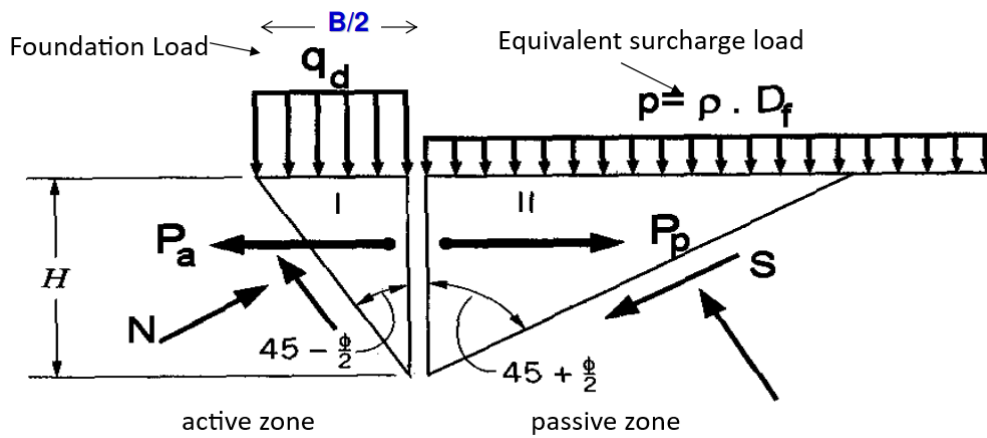


Figure 4: Simplified model

the system to a state of plastic equilibrium—is assumed to act downward on active wedge No. 1, while wedge No. 2 provides passive resistance. Since the load P at the interface represents the plastic equilibrium condition, the system is considered to be failing.

2.1 Terzaghi Method

Terzaghi's bearing capacity equation for shallow foundations:

$$q_{ult} = cN_c s_c + qN_q + 0.5\gamma B N_\gamma s_\gamma \quad (1)$$

In the third term, B' is used. In the equation:

c : In effective stress analysis, it refers to the effective cohesion c' , while in total stress analysis under UU (unconsolidated undrained) conditions, it corresponds to the undrained shear strength $S_u(c_u)$.

N_c : This is the bearing capacity factor. In effective stress analysis, it is calculated based on the effective angle of internal friction ϕ' , while in total stress analysis under UU conditions, it is calculated assuming a friction angle of $\phi = 0$.

N_q : This is the bearing capacity factor. In effective stress analysis, it is calculated based on the effective angle of internal friction ϕ' , whereas in total stress analysis under UU conditions, it is calculated assuming a friction angle of $\phi = 0$.

N_γ : This is the bearing capacity factor. In effective stress analysis, it is calculated based on the effective angle of internal friction ϕ' , whereas in total stress analysis under UU conditions, it is calculated assuming a friction angle of $\phi = 0$.

s_c, s_γ : Shape factors

q : In effective stress analyses, it refers to the effective stress at the foundation base. In total stress analyses, it represents the total stress at the foundation base.

The Terzaghi method provides the bearing capacity of foundations under vertical loading. Eccentricity in both directions can also be taken into account. The condition is $D/B \leq 1$, meaning that the value of D_f cannot exceed the value of B. This condition should also be taken into account when calculating the value of q , including the depth D_f . Shape factors for rectangular foundations are calculated using B' and L' . The third term uses B' . The effect of the water table (Y.A.S.S) is taken into account in the γ value used in the third term. For the case of $\phi = 0$, $N_\gamma = 0$ and $N_q = 1$. When cohesion $c = 0$, the first term becomes zero and is therefore omitted from the equation.

B: Length of the short side of the foundation

L: Length of the long side of the foundation

D_f : Depth of foundation embedment

The effect of the groundwater level is considered in the second term by calculating the effective stress at the foundation base. In the third term, a correction is applied to the value of γ . Depending on the position of the groundwater level (GWT) relative to depth z :

- Case 1: GWT = 0 (at the surface) $\rightarrow \gamma'$ is used.
- Case 2: In the range $0 < \text{GWT} \leq D_f$, γ' is used.
- Case 3: In the range $D_f \leq \text{GWL} \leq B$, the corrected unit weight is calculated using Equation (2).

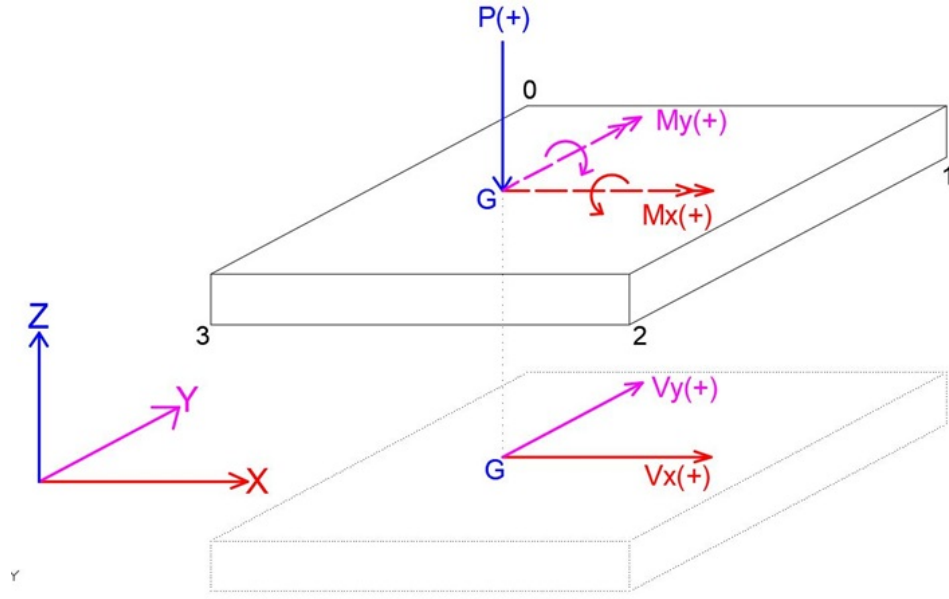


Figure 5: Loads acting on the foundation

$$\bar{\gamma} = \gamma' + \left(\frac{z - D_f}{B} \right) (\gamma - \gamma') \quad (2)$$

Eccentricity

e_x : Eccentricity of the foundation in the x-direction

$$e_x = \frac{M_y}{P} \quad (3)$$

e_y : Eccentricity of the foundation in the y-direction

$$e_y = \frac{M_x}{P} \quad (4)$$

$$L'_x = L_x - 2 \cdot e_x \quad (5)$$

$$L'_y = L_y - 2 \cdot e_y \quad (6)$$

B' : Effective width of the foundation (short side)

$$B' = \text{Min}(L'_x, L'_y) \quad (7)$$

L' : Effective length of the foundation (long side)

$$L' = \text{Maks}(L'_x, L'_y) \quad (8)$$

Applied stress q_a at the foundation base:

$$q_a = \frac{P}{(B' \times L')} \quad (9)$$

Terzaghi Bearing Capacity Factors

$$N_q = \left[\frac{e^{2 \cdot \left(\frac{3\pi}{4} - \frac{\phi}{2}\right) \cdot \tan(\phi)}}{2 \cdot \cos^2 \left(\frac{\pi}{4} + \frac{\phi}{2}\right)} \right] \quad (10)$$

$$N_c = (N_q - 1) \cdot \cot \phi \quad (11)$$

$$N_\gamma = \frac{\tan \phi}{2} \left[\frac{K_{p\gamma}}{\cos^2 \phi} - 1 \right] \quad (12)$$

$$K_{p\gamma} = 3 \tan^2 \left(45 + \frac{\phi + 33}{2} \right) \quad (13)$$

Shape Factors

For rectangular footings:

$$s_c = 1 + 0.2 \left(\frac{B'}{L'} \right) \quad (14)$$

$$s_\gamma = 1 - 0.2 \left(\frac{B'}{L'} \right) \quad (15)$$

For strip footings:

$$s_c = 1 \quad (16)$$

$$s_\gamma = 1 \quad (17)$$

For circular footings:

$$s_c = 1.3 \quad (18)$$

$$s_\gamma = 1.6 \quad (19)$$

2.2 Meyerhof Method

Meyerhof's bearing capacity equation for shallow foundations:

$$q_{ult} = cN_c s_c d_c i_c + qN_q s_q d_q i_q + 0.5\gamma B N_\gamma s_\gamma d_\gamma i_\gamma \quad (20)$$

In the Meyerhof equation, horizontal force can also be considered alongside the vertical load.

Eccentricity is calculated in both directions. When calculating q in the second term, the condition $\frac{D_f}{B} \leq 1$ must be satisfied.

s_c, s_q, s_γ : Shape factors

d_c, d_q, d_γ : Depth factors

i_c, i_q, i_γ : Inclination factors

P : Axial load

The values of B and L are used for the applied stress q_a .

$$q_a = \frac{P}{(BxL)} \quad (21)$$

Bearing Capacity Factors

$$N_q = e^{\pi \tan \phi} \tan^2 \left(45 + \frac{\phi}{2} \right) \quad (22)$$

$$N_c = (N_q - 1) \cot \phi \quad (23)$$

$$N_\gamma = (N_q - 1) \tan (1.4\phi) \quad (24)$$

Shape Factors

$$s_c = 1 + 0.2K_p \frac{B}{L} \quad \text{for any } \phi \quad (25)$$

$$s_q = s_\gamma = 1 + 0.1K_p \frac{B}{L} \quad \phi > 0 \quad (26)$$

$$s_q = s_\gamma = 1 \quad \phi = 0 \quad (27)$$

Depth Factors

$$d_c = 1 + 0.2\sqrt{K_p} \frac{D}{B} \quad \text{for any } \phi \quad (28)$$

$$d_q = d_\gamma = 1 + 0.1\sqrt{K_p} \frac{D}{B} \quad \phi > 0 \quad (29)$$

$$d_q = d_\gamma = 1 \quad \phi = 0 \quad (30)$$

Inclination Factors

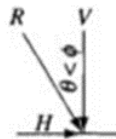


Figure 6: Load inclination

$$i_c = i_q = \left(1 - \frac{\theta^\circ}{90^\circ} \right)^2 \quad \text{for any } \phi \quad (31)$$

$$i_\gamma = \left(1 - \frac{\theta^\circ}{\phi^\circ} \right)^2 \quad \phi > 0 \quad (32)$$

$$i_\gamma = 0 \quad \theta > 0 \quad \text{and} \quad \phi = 0 \quad \text{condition} \quad (33)$$

$$K_p = \tan^2(45 + \phi/2) \quad (34)$$

θ : The angle between the load vector and the vertical. When $\theta = 0$, all i factors are equal to 1.

Reduction in Bearing Capacity

The use of R_e for reduction with the Meyerhof equation has been recommended. This reduction is applied for eccentricity.

$$q_{ult,Re} = q_{ult} \times R_e \quad (35)$$

The reduction factor is given for fine-grained (cohesive soils), sands, and for the condition $0 < \frac{e}{B} < 0.3$, as follows:

$$R_e = 1 - \frac{2e}{B} \quad (\text{clays}) \quad (36)$$

$$R_e = \sqrt{\frac{e}{B}} \quad (\text{sands}) \quad (37)$$

Alternatively, it is possible to calculate the shape and depth factors using B' and L' , and to use B' in the third term. In this case, the applied stress will be $q_a = \frac{P}{B' \times L'}$.

2.3 Vesic Method

The Vesic bearing capacity equation is formulated for the resultant of two horizontal force components. When calculating q in the second term of the equation, the condition $\frac{D}{B} \leq 1$ must be satisfied.

$$q_{ult} = cN_c s_c d_c i_c g_c b_c + qN_q s_q d_q i_q g_q b_q + 0.5\gamma B N_\gamma s_\gamma d_\gamma i_\gamma g_\gamma b_\gamma \quad (38)$$

$$\phi = 0 \rightarrow q_{ult} = 5.14c_u (1 + s_c + d_c - i_c - b_c - g_c) + q \quad (39)$$

s_c, s_q, s_γ : Shape factors

d_c, d_q, d_γ : Depth factors

i_c, i_q, i_γ : Inclination factors

g_c, g_q, g_γ : Ground Factors (base on a slope)

b_c, b_q, b_γ : Base factors (tilted base)

Bearing Capacity Factors

N_c : Same as Meyerhof.

N_q : Same as Meyerhof.

$$N_\gamma = 2(N_q + 1) \tan \phi \quad (40)$$

Shape Factors

$$s_c = 1 + \frac{N_q}{N_c} \cdot \frac{B}{L} \quad (41)$$

For all ϕ values:

$$s_q = 1 + \frac{B}{L} \tan \phi \quad (42)$$

$$s_\gamma = 1 - 0,4 \frac{B}{L} \geq 0,6 \quad (43)$$

Depth Factors

$$d_c = 0.4k \quad (\phi = 0) \quad (44)$$

$$d_c = 1 + 0.4k \quad (45)$$

$$D/B \leq 1 \rightarrow k = D/B \quad (46)$$

$$D/B > 1 \rightarrow k = \tan^{-1}(D/B) \quad (47)$$

The unit of (k) must be in radians.

$$d_q = 1 + 2 \tan \phi (1 - \sin \phi)^2 k \quad (48)$$

For all ϕ values, $d_\gamma = 1$.

Inclination Factors

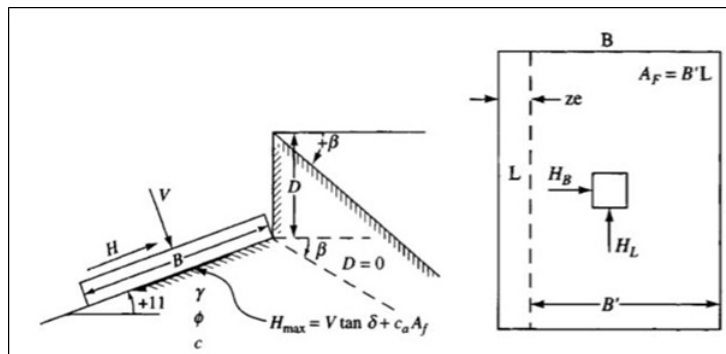


Figure 7: Load inclination factor in the Vesic method

$$A_f = B' L' \quad (49)$$

$$i_c = 1 - \frac{m H_i}{A_f c_a N_c} \quad (\phi = 0) \quad (50)$$

$$i_c = i_q - \frac{1 - i_q}{N_q - 1} \quad (\phi > 0) \quad (51)$$

$$i_q = \left[1 - \frac{H_i}{V + A_f c_a \cot \phi} \right]^m \quad (52)$$

$$i_\gamma = \left[1 - \frac{H_i}{V + A_f c_a \cot \phi} \right]^{m+1} \quad (53)$$

$$m = m_B = \frac{2 + B/L}{1 + B/L} \quad (54)$$

$$m = m_L = \frac{2 + L/B}{1 + L/B} \quad (55)$$

Ground Factors (base on a slope)

$$g_c = \frac{\beta}{5,14} \quad (\phi = 0) \quad (56)$$

The unit of β must be in radians.

$$g_c = i_q - \frac{1 - i_q}{5,14 \tan \phi} \quad (\phi > 0) \quad (57)$$

$$g_q = g_\gamma = (1 - \tan \beta)^2 \quad (58)$$

Base Factors (tilted base)

$$b_c = g_c \quad (\phi = 0) \quad (59)$$

$$b_c = 1 - \frac{2\beta}{5,14 \tan \phi} \quad (60)$$

$$b_q = b_\gamma = (1 - \eta \tan \phi)^2 \quad (61)$$

B and L are used in the shape and depth factors.

3 Bearing Capacity of Deep Foundation

The bearing capacity of deep foundations with rigid columns is calculated using the α , λ , and β methods. Rigid columns can be constructed as concrete/reinforced concrete piles or micropiles, or they can be formed by jet grouting or deep mixing methods.

Characteristic value of compressive resistance of the ground against a rigid column, at the ultimate limit state:

$$R_{c;k} = R_{s;k} + R_{b;k} - W_p \quad (62)$$

$R_{s;k}$: Characteristic value of the shaft resistance of a rigid column

$R_{b;k}$: Characteristic value of the tip resistance of a rigid column

W_p : Net self-weight of rigid column

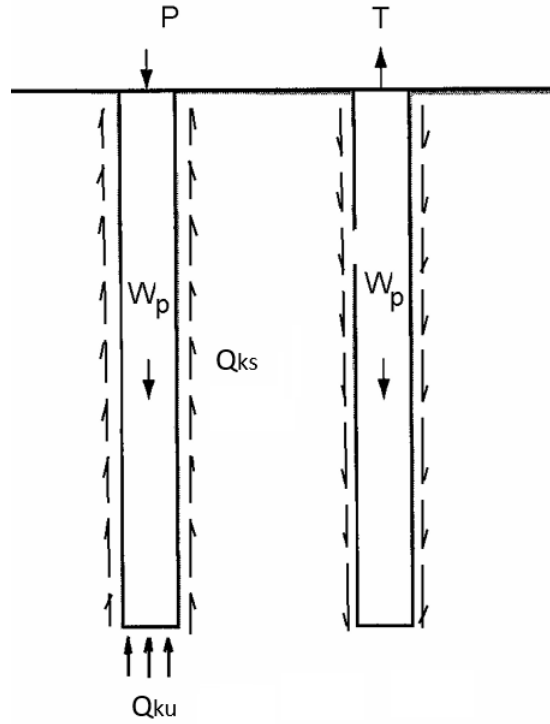


Figure 8: Transfer of structural loads to the soil medium through deep foundations.

3.1 Alpha Method

The α method is used for the short-term bearing capacity of deep foundations. The contribution of soil layers with undrained behavior to the bearing capacity is calculated using this method.

Shaft Resistance

$$f_s = \alpha \times S_u \quad (63)$$

$$\alpha = 0.5\psi^{-0.5} \quad (\psi \leq 1) \quad (64)$$

$$\alpha = 0.5\psi^{-0.25} \quad (\psi > 1) \quad (65)$$

$$A_s = \pi \times D \times L \quad (66)$$

$$Q_s = f_s \times A_s \quad (67)$$

f_s : Shaft frictional stress

S_u : Undrained shear strength

α : Coefficient of adhesion

ψ : The S_u/σ'_0 ratio at the corresponding depth.

A_s : Lateral surface area of column

Q_s : Shaft resistance

Tip Resistance

$$f_b = S_u \times N_c \quad (68)$$

$$R_{b;k} = (S_u \times N_c) A_b \quad (69)$$

A_b : Cross-sectional area of column

f_b : Unit tip resistance of column

N_c : Bearing capacity factor

3.2 Lambda Method

The λ method is used for the short-term bearing capacity of deep foundations. The contribution of soil layers with undrained behavior to the bearing capacity is calculated using this method.

Shaft Resistance

$$f_s = \lambda (\bar{\sigma}'_0 + 2\bar{c}_u) \quad (70)$$

$$\lambda = 0.178 - 0.016 (\ln \pi_3) \quad \text{NC} \quad \text{kil} \quad (71)$$

$$\lambda = 0.232 - 0.0321 (\ln \pi_3) \quad \text{OC} \quad \text{kil} \quad (72)$$

$$\pi_3 = \frac{\pi D f_{\max} L_e^2}{A E_p \mu} \quad (73)$$

$$Q_s = f_s \times A_s \quad (74)$$

f_{\max} : Maksimum sürtünme gerilmesi $\cong c_u$

E_p : Modulus of elasticity of rigid column

D : Diameter of rigid column

L_e : Effective length of the rigid column embedded in the soil

A : Cross-sectional area of rigid column

Tip Resistance

$$f_b = S_u \times N_c \quad (75)$$

$$R_{b;k} = (S_u \times N_c) A_b \quad (76)$$

3.3 Beta Method

The β method is used for the long-term bearing capacity of deep foundations. The contribution of soil layers with drained behavior to the bearing capacity is calculated using this method.

Shaft Resistance

$$f_s = c' + \beta \sigma_0^2 \quad (77)$$

In fine-grained soils:

$$\beta = (1 - \sin \phi') \cdot OCR^{0.5} \cdot \tan \phi' \quad (78)$$

In coarse-grained soils:

$$\beta = (1 - \sin \phi') \tan \phi' \quad (79)$$

$$Q_s = f_s \times A_s \quad (80)$$

Tip Resistance

$$f_b = N_t \cdot \sigma'_{0Df} \quad (81)$$

$$N_t = \left(\tan \phi' + \sqrt{1 + \tan^2 \phi'} \right)^2 e^{2\psi_p \cdot \tan \phi'} \quad (82)$$

$$R_{b;k} = f_b \cdot A_b \quad (83)$$

ψ_p : Plastification angle

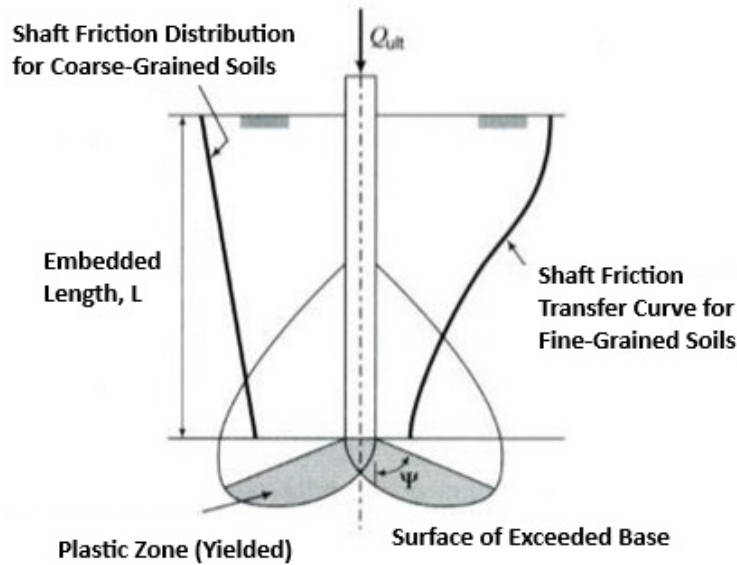


Figure 9: Load transfer characteristics

In soft fine-grained soils, $\psi_p \leq \pi/3$; for soils transitioning from soft fine-grained soils to dense coarse-grained soils and overconsolidated fine-grained soils, $\pi/3 < \psi_p \leq 0.58\pi$; and in dense coarse-grained soils, the value of ψ_p should not exceed $\pi/2$.

3.4 Bearing Capacity of Rigid Column Group

For the bearing capacity of a rigid column group, the group efficiency is calculated either geometrically or using the “Terzaghi Block Behavior” method.

$$R_{c;k,gr} = R_{ck} \cdot n_p \cdot E_g \quad (84)$$

$Q_{ktv,gr}$: Group bearing capacity

n_p : Number of rigid columns

E_g : Group efficiency

Efficiency is calculated from group geometry using the Converse-Labarre method:

$$E_g = 1 - \theta \frac{(n-1)m + (m-1)n}{90mn} \quad (85)$$

using this expression.

$$\theta = \arctan \left(\frac{D}{s} \right) \quad (86)$$

In the Terzaghi block method, the rigid columns and the soil between them are considered as a single block. The ultimate bearing capacity of the column group is calculated using the perimeter and base area of the block. The condition $Q_{ktv,gr} \leq Q_u \times n_p$ is applied.

Note: Differences in rounding and decimal precision may cause deviations in the results ranging from %0.4 - %1. This deviation arises from method and software differences and is considered acceptable for engineering applications. It is not an “error” but an unavoidable difference between high-precision calculations and their simplified/rounded representation.

4 “BLOCK E” Bearing Capacity of Shallow Foundation

The bearing capacity has been calculated using the Vesic method for effective stress analysis.

Foundation Geometry and Base Pressure

$B = 20m$ $L = 32.5m$ $D_f = 4.85m$ $q_0 = 300kN/m^2$ $P = 170000kN$ Foundation base

elevation=-4.85m

Soil Profile

fill: [-0m]-[-4.5m]

$$\gamma_n = 18.5kN/m^3$$

$$\gamma_{sat} = 19.4kN/m^3$$

Effective cohesion $c' = 0kN/m^2$

Internal friction angle for effective stress $\phi' = 26^\circ$

Silty Clay (Alluvium): [-4.5m]-[-9.2m]

$$\gamma_n = 17kN/m^3$$

$$\gamma_{sat} = 17.9kN/m^3$$

Effective cohesion $c' = 4kN/m^2$

Internal friction angle for effective stress $\phi' = 24^\circ$

Gravelly Clayey Sand: [-9.2m]-[-10.5m]

$$\gamma_n = 17.5kN/m^3$$

$$\gamma_{sat} = 19.3kN/m^3$$

Effective cohesion $c' = 1kN/m^2$

Internal friction angle for effective stress $\phi' = 28^\circ$

Clay (Sandy Clay with Silt – SaClSi): [-10.5m]-[-20m]

$$\gamma_n = 18.7kN/m^3$$

$$\gamma_{sat} = 19.5kN/m^3$$

Effective cohesion $c' = 12kN/m^2$

Internal friction angle for effective stress $\phi' = 20^\circ$

Clay 2 (Sandy Clay – SaCl): [-20m]-[-40m]

$$\gamma_n = 18.7kN/m^3$$

$$\gamma_{sat} = 19.5kN/m^3$$

Effective cohesion $c' = 18kN/m^2$

Internal friction angle for effective stress $\phi' = 20^\circ$

Ground Water Table

$$GWT = -2.2m$$

Natural Stress Calculation at Foundation Base Level

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (4.85 - 4.5) \times 17.9 = 91.585kN/m^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (4.85 - 4.5) \times 9.81 = 25.996 \text{ kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (4.85 - 4.5) \times 8.1 = 65.615 \text{ kN/m}^2$$

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The effective foundation dimensions are determined using Equations (6) and (7):

$$B' = 20 \text{ m}$$

$$L' = 32.5 \text{ m}$$

Geotechnical Parameters and Groundwater Table (GWT) Effect

The unit weight of the soil above the foundation base is $\gamma = 13.529 \text{ kN/m}^3$

The effective angle of internal friction of the soil above the foundation base is

$$\phi' = 25.86^\circ = 0.144\pi$$

The weighted average of the effective cohesion of the soil below the foundation base is

$$c' = 11 \text{ kPa}$$

The weighted average of the effective angle of internal friction of the soil below the foundation base is $\phi' = 21.39^\circ = 0.119\pi$

Effect of Groundwater Table

The groundwater effect on γ in the third term has been considered.

For $0 < Y_{ASS} \leq D_f$, the submerged unit weight γ is used. The weighted average submerged unit weight of the soil below the foundation base is $\gamma = 9.339 \text{ kN/m}^3$

Bearing Capacity Factors

The values of N_c , N_q , and N_γ were determined based on Equations (22), (23), and (40).

$$N_q^* = e^{\pi \tan 21.39} \tan^2 \left(45 + \frac{21.39}{2} \right) = 7.35$$

$$N_c = (7.35 - 1) \cot 21.39 = 16.22$$

$$N_q = e^{\pi \tan 25.86} \tan^2 \left(45 + \frac{25.86}{2} \right) = 11.67$$

$$N_\gamma = 2(7.35 + 1) \tan 21.39 = 6.54$$

Shape Factors

The shape factors were calculated using Equations (41), (42), and (43).

$$s_c = 1 + \frac{11.67}{16.22} \cdot \frac{20}{32.5} = 1.44$$

$$s_q = 1 + \frac{20}{32.5} \tan 25.86 = 1.3$$

$$s_\gamma = \max \left(1 - 0.4 \times \frac{20}{32.5} = 0.75; 0.6 \right) = 0.75$$

Depth Factors

Based on the calculations performed according to Equations (45), (46), (47) and (48):

$$\frac{4.85}{20} \leq 1 \rightarrow k = \frac{4.85}{20} = 0.2425$$

$$d_c = 1 + 0.4 \times 0.24 = 1.1$$

$$d_q = 1 + 2 \times \tan 25.86 \times (1 - \sin 25.86)^2 \times 0.24 = 1.07$$

$$d_\gamma = 1$$

Inclination Factors

Since there is no load inclination, the value of these factors is equal to 1.

$$i_q = 1$$

$$i_c = 1$$

$$i_\gamma = 1$$

Ground Factors (base on a slope)

Since there is no ground slope ($\beta = 0$), the value of these factors is equal to 1.

$$g_c = 1$$

$$g_q = 1$$

$$g_\gamma = 1$$

Base Factors (tilted base)

Taban eğimi olmadığı için ($\eta = 0$) bu faktörlerin değeri 1'e eşittir.

$$b_c = 1$$

$$b_q = 1$$

$$b_\gamma = 1$$

Bearing Capacity

$$c' = 11kPa$$

$$\phi' = 25.86^\circ (\text{for soil above the foundation base})$$

$$\phi' = 21.39^\circ (\text{for soil below the foundation base})$$

$$q = 65.61kN/m^2$$

$$N_c = 16.22 \quad N_q = 11.67 \quad N_\gamma = 6.54$$

$$s_c = 1.44 \quad s_q = 1.3 \quad s_\gamma = 0.75$$

$$d_c = 1.1 \quad d_q = 1.07 \quad d_\gamma = 1$$

$$i_c = 1 \quad i_q = 1 \quad i_\gamma = 1$$

$$g_c = 1 \quad g_q = 1 \quad g_\gamma = 1$$

$$b_c = 1 \quad b_q = 1 \quad b_\gamma = 1$$

$$B = 20m \quad B' = 20m \quad \gamma = 9.339kN/m^3$$

Based on effective stresses, the Vesic bearing capacity according to Equation (38):

$$q_{ult} = cN_c s_c d_c i_c g_c b_c + qN_q s_q d_q i_q g_q b_q + 0.5\gamma B N_\gamma s_\gamma d_\gamma i_\gamma g_\gamma b_\gamma$$

$$\begin{aligned} q_{ult} &= 11 \times 16.22 \times 1.44 \times 1.1 \times 1 \times 1 \times 1 \\ &\quad + 65.61 \times 11.67 \times 1.3 \times 1.07 \times 1 \times 1 \times 1 \\ &\quad + 0.5 \times 9.339 \times 20 \times 6.54 \times 0.75 \times 1 \times 1 \times 1 \times 1 \\ &= 1811.8kN/m^2 \end{aligned}$$

Design

$$\text{Contact Pressure } q_0 = 300kN/m^2$$

$$\text{Partial factor } \gamma_{R;v} = 1.4$$

Design bearing capacity (based on effective stresses):

$$q_t = \frac{q_{ult}}{\gamma_{R;v}} = \frac{1811.8}{1.4} = 1294.14kN$$

$$q_0 = 300kN/m^2 \leq q_t = 1294.14kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{q_{ult}}{q_0} = \frac{1811.8}{300} = 6.04$$

5 Bearing Capacity of “BLOCK E” Deep Foundation

Rigid column type: Jet grouting

Number of rigid columns= 187

Diameter of rigid column D= 60cm

Length of rigid column L= 17m

Rigid Column Cap

Geometry: Polygon

Coordinates of the rigid column cap: Polygon1: p1(X= 17.8936m Y= 39.4755m) ; p2(X= 10.881m Y= 71.2099m) ; p3(X= 30.4099m Y= 75.5253m) ; p4(X= 37.4224m Y= 43.791m) ;

Shaft Resistance of a Single Column

Shaft resistance is calculated individually for each soil layer interacting with the column, and their sum gives the total shaft resistance of the column.

- **Interacting Layer 1: [-4.85m] ↔ [-9.2m]**

Soil: Silty Clay (Alluvium)

Effective column length in rigid column/soil interaction zone $L_e = 4.35\text{m}$

$$\gamma_{sat} = 17.9\text{kN/m}^3 \quad \gamma_n = 17\text{kN/m}^3 \quad \gamma_w = 9.81\text{kN/m}^3 \quad \gamma' = 8.1\text{kN/m}^3$$

$$c' = 4\text{kPa} \quad \phi' = 24^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 24) \times 3^{0.5} \times \tan 24 = 0.46$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (7.025 - 4.5) \times 17.9 = 130.518\text{kN/m}^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (7.025 - 4.5) \times 9.81 = 47.333\text{kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (7.025 - 4.5) \times 8.1 = 83.232\text{kN/m}^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 4 + 0.46 \times 83.23 = 42.08kN/m^2$$

Lateral surface area of the rigid column:

$$A_s = \pi DL_e = \pi \times 0.6 \times 4.35 = 8.2m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 42.08 \times 8.2 = 345.03kN$$

• **Interacting Layer 2: [-9.2m] ↔ [-10.5m]**

Soil: Gravelly Clayey Sand

Effective column length in rigid column/soil interaction zone $L_e = 1.3m$

$$\gamma_{sat} = 19.3kN/m^3 \quad \gamma_n = 17.5kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 9.5kN/m^3$$

$$c' = 1kPa \quad \phi' = 28^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 28) \times 3^{0.5} \times \tan 28 = 0.49$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma &= +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 \\ &+ (9.2 - 4.5) \times 17.9 + (9.85 - 9.2) \times 19.3 = 181.995kN/m^2 \end{aligned}$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (9.85 - 9.2) \times 9.81 = 75.046kN/m^2$$

Effective stress:

$$\begin{aligned} \sigma' &= +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 \\ &+ (9.2 - 4.5) \times 8.1 + (9.85 - 9.2) \times 9.5 = 107.025kN/m^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 1 + 0.49 \times 107.02 = 53.29kN/m^2$$

Lateral surface area of the rigid column:

$$A_s = \pi DL_e = \pi \times 0.6 \times 1.3 = 2.45m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 53.29 \times 2.45 = 130.59kN$$

• **Interacting Layer 3: [-10.5m] ↔ [-20m]**

Soil: Clay (Sandy Clay with Silt – SaClSi)

Effective column length in rigid column/soil interaction zone $L_e = 9.5m$

$$\gamma_{sat} = 19.5kN/m^3 \quad \gamma_n = 18.7kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 9.7kN/m^3$$

$$c' = 12kPa \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma &= +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 \\ &+ (10.5 - 9.2) \times 19.3 + (15.25 - 10.5) \times 19.5 = 287.165kN/m^2 \end{aligned}$$

Pore water pressure:

$$\begin{aligned} u_w &= +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 \\ &+ (10.5 - 9.2) \times 9.81 + (15.25 - 10.5) \times 9.81 = 128.02kN/m^2 \end{aligned}$$

Effective stress:

$$\begin{aligned} \sigma' &= +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 \\ &+ (10.5 - 9.2) \times 9.5 + (15.25 - 10.5) \times 9.7 = 159.275kN/m^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 12 + 0.41 \times 159.28 = 78.07kN/m^2$$

Lateral surface area of the rigid column:

$$A_s = \pi DL_e = \pi \times 0.6 \times 9.5 = 17.91m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 78.07 \times 17.91 = 1397.96kN$$

• **Interacting Layer 4: [-20m] ↔ [-21.85m]**

Soil: Clay 2 (Sandy Clay – SaCl)

Effective column length in rigid column/soil interaction zone $L_e = 1.85m$

$$\gamma_{sat} = 19.5kN/m^3 \quad \gamma_n = 18.7kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 9.7kN/m^3$$

$$c' = 18kPa \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (20 - 10.5) \times 19.5 + (20.925 - 20) \times 19.5 = 397.828kN/m^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ + (20 - 10.5) \times 9.81 + (20.925 - 20) \times 9.81 = 183.692kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (20 - 10.5) \times 9.7 + (20.925 - 20) \times 9.7 = 214.322kN/m^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 18 + 0.41 \times 214.32 = 106.9kN/m^2$$

Lateral surface area of the rigid column:

$$A_s = \pi DL_e = \pi \times 0.6 \times 1.85 = 3.49m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 106.9 \times 3.49 = 372.78kN$$

• Total Shaft Resistance

Shaft resistances of all rigid column/soil interaction layers are summed.

$$R_{s;k} = \sum_{i=1}^4 Q_{si} = 345.03 + 130.59 + 1397.96 + 372.78 = \mathbf{2246.35kN}$$

Tip Resistance of a Single Column

Effective shear strength angle at the column tip: $\phi' = 20^\circ$

Tip elevation of the rigid column = -21.85m

Natural stresses at the tip of the rigid column have been calculated.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (20 - 10.5) \times 19.5 + (21.85 - 20) \times 19.5 = 415.865kN/m^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ + (20 - 10.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (20 - 10.5) \times 9.7 + (21.85 - 20) \times 9.7 = 223.295kN/m^2$$

Plastification angle $\psi_p = 0.4\pi$

Tip resistance was calculated for effective stresses using Equations (81), (82), and (83).

$$N_t = \left(\tan 20 + \sqrt{1 + \tan^2 20} \right)^2 e^{2 \times 0.4\pi \times \tan 20} = 5.091$$

$$f_b = 5.091 \times 223.3 = 1136.82kN/m^2$$

Cross-sectional area of the rigid column:

$$A_b = \frac{\pi D^2}{4} = \frac{\pi \times 0.6^2}{4} = 0.28m^2$$

Tip resistance:

$$R_{b;k} = 1136.82 \times 0.28 = \mathbf{318.32kN}$$

Bearing Capacity of a Single Column

The unit weight of a jet grouting column is calculated as the weighted average of the unit weights of the mixtures in the interacting soil layers.

$$\gamma_{c,av} = \frac{\sum_{i=1}^7 \gamma_{mix,i} \times L_{e,i}}{L_p} = \frac{22 \times 4.35 + 22 \times 1.3 + 22 \times 9.5 + 22 \times 1.85}{17} = 22kN/m^3$$

$$W_p = \gamma_{c,av} L_p A_b = 22 \times 17 \times 0.28 = 105.75kN$$

Pore water pressure at the tip of the rigid column:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ + (20 - 10.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766kN/m^2$$

The net self-weight of the column is determined by taking into account the pore water pressure at the column tip.

$$W_{p,net} = W_p - u_w \times A_b = 105.75 - 192.77 \times 0.28 = 51.77kN$$

Bearing capacity was obtained by applying Equation (62).

$$R_{c;k} = R_{s;k} + R_{b;k} - W_p = 2246.35 + 318.32 - 51.77 = \mathbf{2512.9kN}$$

Design of a Single Column

Design axial load on the rigid column:: $F_{c;d} = 1024.45kN$

Partial factors: $\gamma_s = 1.5$ $\gamma_b = 2$

Design bearing capacity:

$$R_{c;d} = \frac{R_{s;k}}{\gamma_{Rs}} + \frac{R_{b;k}}{\gamma_{Ru}} = \frac{2246.35}{1.5} + \frac{318.32}{2} = \mathbf{1656.73kN}$$

$$F_{c;d} = 1024.45kN/m^2 \leq R_{c;d} = 1656.73kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{R_{c;k}}{F_{c;d}} = \frac{2512.9}{1024.45} = 2.45$$

Bearing Capacity of Rigid Column Group

The bearing capacity of the rigid column group was calculated using the Terzaghi block method.

Block Shaft Resistance

Shaft resistance is calculated individually for each soil layer interacting with the column, and their sum gives the total shaft resistance of the block.

- **Interacting Layer 1: [-4.85m] ↔ [-9.2m]**

Soil: Silty Clay (Alluvium)

Effective column length in block/soil interaction zone $L_e = 4.35\text{m}$

$$\gamma_{sat} = 17.9\text{kN/m}^3 \quad \gamma_n = 17\text{kN/m}^3 \quad \gamma_w = 9.81\text{kN/m}^3 \quad \gamma' = 8.1\text{kN/m}^3$$

$$c' = 4\text{kPa} \quad \phi' = 24^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 24) \times 3^{0.5} \times \tan 24 = 0.46$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (7.025 - 4.5) \times 17.9 = 130.518\text{kN/m}^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (7.025 - 4.5) \times 9.81 = 47.333\text{kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (7.025 - 4.5) \times 8.1 = 83.232\text{kN/m}^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 4 + 0.46 \times 83.23 = 42.08\text{kN/m}^2$$

Block perimeter $\xi = 105\text{m}$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 105 \times 4.35 = 456.75\text{m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 42.08 \times 456.75 = 19219.49\text{kN}$$

• **Interacting Layer 2: [-9.2m] ↔ [-10.5m]**

Soil: Gravelly Clayey Sand

Effective column length in block/soil interaction zone $L_e = 1.3\text{m}$

$$\gamma_{sat} = 19.3\text{kN/m}^3 \quad \gamma_n = 17.5\text{kN/m}^3 \quad \gamma_w = 9.81\text{kN/m}^3 \quad \gamma' = 9.5\text{kN/m}^3$$

$$c' = 1\text{kPa} \quad \phi' = 28^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 28) \times 3^{0.5} \times \tan 28 = 0.49$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma &= +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 \\ &+ (9.2 - 4.5) \times 17.9 + (9.85 - 9.2) \times 19.3 = 181.995\text{kN/m}^2 \end{aligned}$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (9.85 - 9.2) \times 9.81 = 75.046\text{kN/m}^2$$

Effective stress:

$$\begin{aligned} \sigma' &= +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 \\ &+ (9.2 - 4.5) \times 8.1 + (9.85 - 9.2) \times 9.5 = 107.025\text{kN/m}^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 1 + 0.49 \times 107.02 = 53.29\text{kN/m}^2$$

Block perimeter $\xi = 105\text{m}$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 105 \times 1.3 = 136.5\text{m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 53.29 \times 136.5 = 7274.24\text{kN}$$

• **Interacting Layer 3: [-10.5m] ↔ [-20m]**

Soil: Clay (Sandy Clay with Silt – SaClSi)

Effective column length in block/soil interaction zone $L_e = 9.5\text{m}$

$$\gamma_{sat} = 19.5\text{kN/m}^3 \quad \gamma_n = 18.7\text{kN/m}^3 \quad \gamma_w = 9.81\text{kN/m}^3 \quad \gamma' = 9.7\text{kN/m}^3$$

$$c' = 12\text{kPa} \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma = & +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 \\ & + (10.5 - 9.2) \times 19.3 + (15.25 - 10.5) \times 19.5 = 287.165\text{kN/m}^2 \end{aligned}$$

Pore water pressure:

$$\begin{aligned} u_w = & +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 \\ & + (10.5 - 9.2) \times 9.81 + (15.25 - 10.5) \times 9.81 = 128.02\text{kN/m}^2 \end{aligned}$$

Effective stress:

$$\begin{aligned} \sigma' = & +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 \\ & + (10.5 - 9.2) \times 9.5 + (15.25 - 10.5) \times 9.7 = 159.275\text{kN/m}^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 12 + 0.41 \times 159.28 = 78.07\text{kN/m}^2$$

Block perimeter $\xi = 105\text{m}$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 105 \times 9.5 = 997.5\text{m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 78.07 \times 997.5 = 77872\text{kN}$$

• **Interacting Layer 4: [-20m] ↔ [-21.85m]**

Soil: Clay 2 (Sandy Clay – SaCl)

Effective column length in block/soil interaction zone $L_e = 1.85\text{m}$

$$\gamma_{sat} = 19.5\text{kN/m}^3 \quad \gamma_n = 18.7\text{kN/m}^3 \quad \gamma_w = 9.81\text{kN/m}^3 \quad \gamma' = 9.7\text{kN/m}^3$$

$$c' = 18\text{kPa} \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma = & +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ & + (20 - 10.5) \times 19.5 + (20.925 - 20) \times 19.5 = 397.828\text{kN/m}^2 \end{aligned}$$

Pore water pressure:

$$\begin{aligned} u_w = & +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ & + (20 - 10.5) \times 9.81 + (20.925 - 20) \times 9.81 = 183.692\text{kN/m}^2 \end{aligned}$$

Effective stress:

$$\begin{aligned} \sigma' = & +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ & + (20 - 10.5) \times 9.7 + (20.925 - 20) \times 9.7 = 214.322\text{kN/m}^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 18 + 0.41 \times 214.32 = 106.9\text{kN/m}^2$$

Block perimeter $\xi = 105\text{m}$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 105 \times 1.85 = 194.25\text{m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 106.9 \times 194.25 = 20765.49\text{kN}$$

• Total Shaft Resistance

Shaft resistances of all block/soil interaction layers are summed.

$$R_{s;k,gr} = \sum_{i=1}^4 Q_{si} = 19219.49 + 7274.24 + 77872 + 20765.49 = \mathbf{125131.22kN}$$

Block Base Resistance

Effective shear strength angle at the block base: $\phi' = 20^\circ$

Elevation at the block base = -21.85m

Natural stresses at the block base have been calculated.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (20 - 10.5) \times 19.5 + (21.85 - 20) \times 19.5 = 415.865kN/m^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ + (20 - 10.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (20 - 10.5) \times 9.7 + (21.85 - 20) \times 9.7 = 223.295kN/m^2$$

Plastification angle $\psi_p = 0.4\pi$

Block base resistance was calculated for effective stresses using Equations (81), (82), and (83).

$$N_t = \left(\tan 20 + \sqrt{1 + \tan^2 20} \right)^2 e^{2 \times 0.4\pi \times \tan 20} = 5.091$$

$$f_b = 5.091 \times 223.3 = 1136.82kN/m^2$$

Block base area:

$$A_b = 650m^2$$

Base resistance:

$$R_{b;k,gr} = 1136.82 \times 650 = \mathbf{738943.34kN}$$

Block Bearing Capacity

Self-weight of the rigid columns within the block:

$$W_{p,b} = n_p \times W_p = 187 \times 105.75 = 19774.5kN$$

Area of the soil enclosed within the block:

$$A_s = Ab - n_p \times \left(\frac{\pi \times D^2}{4} \right) = 650 - 187 \times \left(\frac{\pi \times 0.6^2}{4} \right) = 597.12m^2$$

Self-weight of the soil enclosed within the block:

$$W_{s,b} = \sum_1^{10} \gamma_{n,i} L_{e,i} A_s = 17 \times 4.35 \times 597.12 + 17.5 \times 1.3 \times 597.12 + 18.7 \times 9.5 \times 597.12 + 18.7 \times 1.85 \times 597.12 + = 184478.68kN$$

Self-weight of the block:

$$W_b = W_{p,b} + W_{s,b} = 19774.5 + 184478.68 = 204253.18kN$$

Pore water pressure at the block base:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 + (20 - 10.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766kN/m^2$$

The net self-weight of the block is determined by taking into account the pore water pressure at the base.

$$W_{b,net} = W_b - u_w \times A_b = 204253.18 - 192.77 \times 650 = 78955.41kN$$

Bearing capacity was obtained by applying Equation (62).

$$R_{c;k,gr} = R_{s;k,gr} + R_{b;k,gr} - W_b = 125131.22 + 738943.34 - 78955.41 = \mathbf{785119.16kN}$$

The group efficiency has been limited to 1 in order to remain on the safe side.

$$R_{c;k,gr} = n \times R_{c;k} = 187 \times 2512.9 = 469912.05kN$$

Design of Rigid Column Group

Axial design load on the rigid column group: $F_{c;d,gr} = 170000kN$

Partial factor $\gamma_R = 1.5$

Design group bearing capacity:

$$R_{c;d,gr} = \frac{R_{c;k,gr}}{\gamma_R} = \frac{469912.05}{1.5} = \mathbf{313274.7kN}$$

$$F_{c;d,gr} = 170000kN/m^2 \leq R_{c;d} = 313274.7kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{R_{c;k,gr}}{F_{c;d,gr}} = \frac{469912.05}{170000} = 2.76$$

6 “BLOCK E” Combined Bearing Capacity

The combined bearing capacity of the foundation system resting on rigid columns is being evaluated. The total capacity is obtained by combining the previously calculated shallow foundation bearing capacity with the bearing capacity of the rigid column group.

Combined bearing capacity:

$$q_{ult,comb} = q_{ult} + \frac{R_{c;k,gr}}{A} = 1811.8 + \frac{469912.05}{650} = \mathbf{2534.74kN/m^2}$$

Design combined bearing capacity:

$$q_{t,comb} = q_t + \frac{R_{c;d,gr}}{A} = 1294.14 + \frac{313274.7}{650} = \mathbf{1776.11kN/m^2}$$

7 “BLOCK D” Bearing Capacity of Shallow Foundation

The bearing capacity has been calculated using the Vesic method for effective stress analysis.

Foundation Geometry and Base Pressure

$B = 20m$ $L = 30m$ $D_f = 4.85m$ $q_0 = 300kN/m^2$ $P = 170000kN$ Foundation base elevation=-4.85m

Soil Profile

fill: [-0m]-[-4.5m]

$$\gamma_n = 18.5kN/m^3$$

$$\gamma_{sat} = 19.4kN/m^3$$

Effective cohesion $c' = 0kN/m^2$

Internal friction angle for effective stress $\phi' = 26^\circ$

Silty Clay (Alluvium): [-4.5m]-[-9.2m]

$$\gamma_n = 17kN/m^3$$

$$\gamma_{sat} = 17.9kN/m^3$$

Effective cohesion $c' = 4kN/m^2$

Internal friction angle for effective stress $\phi' = 24^\circ$

Gravelly Clayey Sand: [-9.2m]-[-10.5m]

$$\gamma_n = 17.5kN/m^3$$

$$\gamma_{sat} = 19.3kN/m^3$$

Effective cohesion $c' = 1kN/m^2$

Internal friction angle for effective stress $\phi' = 28^\circ$

Clay (Sandy Clay with Silt – SaClSi): [-10.5m]-[-20m]

$$\gamma_n = 18.7kN/m^3$$

$$\gamma_{sat} = 19.5kN/m^3$$

Effective cohesion $c' = 12kN/m^2$

Internal friction angle for effective stress $\phi' = 20^\circ$

Clay 2 (Sandy Clay – SaCl): [-20m]-[-40m]

$$\gamma_n = 18.7kN/m^3$$

$$\gamma_{sat} = 19.5kN/m^3$$

Effective cohesion $c' = 18kN/m^2$

Internal friction angle for effective stress $\phi' = 20^\circ$

Ground Water Table

$$GWT = -2.2m$$

Natural Stress Calculation at Foundation Base Level

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (4.85 - 4.5) \times 17.9 = 91.585kN/m^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (4.85 - 4.5) \times 9.81 = 25.996kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (4.85 - 4.5) \times 8.1 = 65.615kN/m^2$$

Eksantrisine

The effective foundation dimensions are determined using Equations (6) and (7):

$$B' = 20m$$

$$L' = 30m$$

Geotechnical Parameters and Groundwater Table (GWT) Effect

The unit weight of the soil above the foundation base is $\gamma = 13.529kN/m^3$

The effective angle of internal friction of the soil above the foundation base is

$$\phi' = 25.86^\circ = 0.144\pi$$

The weighted average of the effective cohesion of the soil below the foundation base is

$$c' = 11kPa$$

The weighted average of the effective angle of internal friction of the soil below the foundation

$$\text{base is } \phi' = 21.39^\circ = 0.119\pi$$

Effect of Groundwater Table

The groundwater effect on γ in the third term has been considered.

For $0 < Y_{ASS} \leq D_f$, the submerged unit weight γ is used. The weighted average submerged unit weight of the soil below the foundation base is $\gamma = 9.339kN/m^3$

Bearing Capacity Factors

The values of N_c , N_q , and N_γ were determined based on Equations (22), (23), and (40).

$$N_q^* = e^{\pi \tan 21.39} \tan^2 \left(45 + \frac{21.39}{2} \right) = 7.35$$

$$N_c = (7.35 - 1) \cot 21.39 = 16.22$$

$$N_q = e^{\pi \tan 25.86} \tan^2 \left(45 + \frac{25.86}{2} \right) = 11.67$$

$$N_\gamma = 2(7.35 + 1) \tan 21.39 = 6.54$$

Shape Factors

The shape factors were calculated using Equations (41), (42), and (43).

$$s_c = 1 + \frac{11.67}{16.22} \cdot \frac{20}{30} = 1.48$$

$$s_q = 1 + \frac{20}{30} \tan 25.86 = 1.32$$

$$s_\gamma = \max \left(1 - 0.4 \times \frac{20}{30} = 0.73; 0.6 \right) = 0.73$$

Depth Factors

Based on the calculations performed according to Equations (45), (46), (47) and (48):

$$\frac{4.85}{20} \leq 1 \rightarrow k = \frac{4.85}{20} = 0.2425$$

$$d_c = 1 + 0.4 \times 0.24 = 1.1$$

$$d_q = 1 + 2 \times \tan 25.86 \times (1 - \sin 25.86)^2 \times 0.24 = 1.07$$

$$d_\gamma = 1$$

Inclination Factors

Since there is no load inclination, the value of these factors is equal to 1.

$$i_q = 1$$

$$i_c = 1$$

$$i_\gamma = 1$$

Ground Factors (base on a slope)

Since there is no ground slope ($\beta = 0$), the value of these factors is equal to 1.

$$g_c = 1$$

$$g_q = 1$$

$$g_\gamma = 1$$

Base Factors (tilted base)

Taban eğimi olmadığı için ($\eta = 0$) bu faktörlerin değeri 1'e eşittir.

$$b_c = 1$$

$$b_q = 1$$

$$b_\gamma = 1$$

Bearing Capacity

$$c' = 11kPa$$

$$\phi' = 25.86^\circ (\text{for soil above the foundation base})$$

$$\phi' = 21.39^\circ (\text{for soil below the foundation base})$$

$$q = 65.61kN/m^2$$

$$N_c = 16.22 \quad N_q = 11.67 \quad N_\gamma = 6.54$$

$$s_c = 1.48 \quad s_q = 1.32 \quad s_\gamma = 0.73$$

$$d_c = 1.1 \quad d_q = 1.07 \quad d_\gamma = 1$$

$$i_c = 1 \quad i_q = 1 \quad i_\gamma = 1$$

$$g_c = 1 \quad g_q = 1 \quad g_\gamma = 1$$

$$b_c = 1 \quad b_q = 1 \quad b_\gamma = 1$$

$$B = 20m \quad B' = 20m \quad \gamma = 9.339kN/m^3$$

Based on effective stresses, the Vesic bearing capacity according to Equation (38):

$$q_{ult} = cN_c s_c d_c i_c g_c b_c + qN_q s_q d_q i_q g_q b_q + 0.5\gamma B N_\gamma s_\gamma d_\gamma i_\gamma g_\gamma b_\gamma$$

$$\begin{aligned} q_{ult} &= 11 \times 16.22 \times 1.48 \times 1.1 \times 1 \times 1 \times 1 \\ &\quad + 65.61 \times 11.67 \times 1.32 \times 1.07 \times 1 \times 1 \times 1 \\ &\quad + 0.5 \times 9.339 \times 20 \times 6.54 \times 0.73 \times 1 \times 1 \times 1 \times 1 \\ &= 1826.95 kN/m^2 \end{aligned}$$

Design

Contact Pressure $q_0 = 300 kN/m^2$

Partial factor $\gamma_{R,v} = 1.4$

Design bearing capacity (based on effective stresses):

$$q_t = \frac{q_{ult}}{\gamma_{R,v}} = \frac{1826.95}{1.4} = 1304.96 kN$$

$$q_0 = 300 kN/m^2 \leq q_t = 1304.96 kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{q_{ult}}{q_0} = \frac{1826.95}{300} = 6.09$$

8 Bearing Capacity of “BLOCK D” Deep Foundation

Rigid column type: Jet grouting

Number of rigid columns= 176

Diameter of rigid column D= 60cm

Length of rigid column L= 17m

Rigid Column Cap

Geometry: Polygon

Coordinates of the rigid column cap: Polygon1: p1(X= 48.6003m Y= 48.8213m) ; p2(X= 42.1272m Y= 78.1146m) ; p3(X= 61.6561m Y= 82.43m) ; p4(X= 68.1292m Y= 53.1367m) ;

Shaft Resistance of a Single Column

Shaft resistance is calculated individually for each soil layer interacting with the column, and their sum gives the total shaft resistance of the column.

- **Interacting Layer 1: [-4.85m] ↔ [-9.2m]**

Soil: Silty Clay (Alluvium)

Effective column length in rigid column/soil interaction zone $L_e = 4.35\text{m}$

$$\gamma_{sat} = 17.9\text{kN/m}^3 \quad \gamma_n = 17\text{kN/m}^3 \quad \gamma_w = 9.81\text{kN/m}^3 \quad \gamma' = 8.1\text{kN/m}^3$$

$$c' = 4\text{kPa} \quad \phi' = 24^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 24) \times 3^{0.5} \times \tan 24 = 0.46$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (7.025 - 4.5) \times 17.9 = 130.518\text{kN/m}^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (7.025 - 4.5) \times 9.81 = 47.333\text{kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (7.025 - 4.5) \times 8.1 = 83.232\text{kN/m}^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 4 + 0.46 \times 83.23 = 42.08\text{kN/m}^2$$

Lateral surface area of the rigid column:

$$A_s = \pi D L_e = \pi \times 0.6 \times 4.35 = 8.2\text{m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 42.08 \times 8.2 = 345.03\text{kN}$$

- **Interacting Layer 2: [-9.2m] ↔ [-10.5m]**

Soil: Gravelly Clayey Sand

Effective column length in rigid column/soil interaction zone $L_e = 1.3\text{m}$

$$\gamma_{sat} = 19.3kN/m^3 \quad \gamma_n = 17.5kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 9.5kN/m^3$$

$$c' = 1kPa \quad \phi' = 28^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 28) \times 3^{0.5} \times \tan 28 = 0.49$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma &= +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 \\ &+ (9.2 - 4.5) \times 17.9 + (9.85 - 9.2) \times 19.3 = 181.995kN/m^2 \end{aligned}$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (9.85 - 9.2) \times 9.81 = 75.046kN/m^2$$

Effective stress:

$$\begin{aligned} \sigma' &= +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 \\ &+ (9.2 - 4.5) \times 8.1 + (9.85 - 9.2) \times 9.5 = 107.025kN/m^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 1 + 0.49 \times 107.02 = 53.29kN/m^2$$

Lateral surface area of the rigid column:

$$A_s = \pi DL_e = \pi \times 0.6 \times 1.3 = 2.45m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 53.29 \times 2.45 = 130.59kN$$

- **Interacting Layer 3: [-10.5m] ↔ [-20m]**

Soil: Clay (Sandy Clay with Silt – SaClSi)

Effective column length in rigid column/soil interaction zone $L_e = 9.5m$

$$\gamma_{sat} = 19.5kN/m^3 \quad \gamma_n = 18.7kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 9.7kN/m^3$$

$$c' = 12 \text{ kPa} \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma = & +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 \\ & + (10.5 - 9.2) \times 19.3 + (15.25 - 10.5) \times 19.5 = 287.165 \text{ kN/m}^2 \end{aligned}$$

Pore water pressure:

$$\begin{aligned} u_w = & +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 \\ & + (10.5 - 9.2) \times 9.81 + (15.25 - 10.5) \times 9.81 = 128.02 \text{ kN/m}^2 \end{aligned}$$

Effective stress:

$$\begin{aligned} \sigma' = & +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 \\ & + (10.5 - 9.2) \times 9.5 + (15.25 - 10.5) \times 9.7 = 159.275 \text{ kN/m}^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 12 + 0.41 \times 159.28 = 78.07 \text{ kN/m}^2$$

Lateral surface area of the rigid column:

$$A_s = \pi D L_e = \pi \times 0.6 \times 9.5 = 17.91 \text{ m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 78.07 \times 17.91 = 1397.96 \text{ kN}$$

- **Interacting Layer 4: [-20m] ↔ [-21.85m]**

Soil: Clay 2 (Sandy Clay – SaCl)

Effective column length in rigid column/soil interaction zone $L_e = 1.85 \text{ m}$

$$\gamma_{sat} = 19.5 \text{ kN/m}^3 \quad \gamma_n = 18.7 \text{ kN/m}^3 \quad \gamma_w = 9.81 \text{ kN/m}^3 \quad \gamma' = 9.7 \text{ kN/m}^3$$

$$c' = 18 \text{ kPa} \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma = & +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ & + (20 - 10.5) \times 19.5 + (20.925 - 20) \times 19.5 = 397.828 \text{ kN/m}^2 \end{aligned}$$

Pore water pressure:

$$\begin{aligned} u_w = & +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ & + (20 - 10.5) \times 9.81 + (20.925 - 20) \times 9.81 = 183.692 \text{ kN/m}^2 \end{aligned}$$

Effective stress:

$$\begin{aligned} \sigma' = & +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ & + (20 - 10.5) \times 9.7 + (20.925 - 20) \times 9.7 = 214.322 \text{ kN/m}^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 18 + 0.41 \times 214.32 = 106.9 \text{ kN/m}^2$$

Lateral surface area of the rigid column:

$$A_s = \pi DL_e = \pi \times 0.6 \times 1.85 = 3.49 \text{ m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 106.9 \times 3.49 = 372.78 \text{ kN}$$

• Total Shaft Resistance

Shaft resistances of all rigid column/soil interaction layers are summed.

$$R_{s;k} = \sum_{i=1}^4 Q_{si} = 345.03 + 130.59 + 1397.96 + 372.78 = \mathbf{2246.35 \text{ kN}}$$

Tip Resistance of a Single Column

Effective shear strength angle at the column tip: $\phi' = 20^\circ$

Tip elevation of the rigid column = -21.85m

Natural stresses at the tip of the rigid column have been calculated.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (20 - 10.5) \times 19.5 + (21.85 - 20) \times 19.5 = 415.865 \text{ kN/m}^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ + (20 - 10.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766 \text{ kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (20 - 10.5) \times 9.7 + (21.85 - 20) \times 9.7 = 223.295 \text{ kN/m}^2$$

Plastification angle $\psi_p = 0.4\pi$

Tip resistance was calculated for effective stresses using Equations (81), (82), and (83).

$$N_t = \left(\tan 20 + \sqrt{1 + \tan^2 20} \right)^2 e^{2 \times 0.4\pi \times \tan 20} = 5.091 \\ f_b = 5.091 \times 223.3 = 1136.82 \text{ kN/m}^2$$

Cross-sectional area of the rigid column:

$$A_b = \frac{\pi D^2}{4} = \frac{\pi \times 0.6^2}{4} = 0.28 \text{ m}^2$$

Tip resistance:

$$R_{b;k} = 1136.82 \times 0.28 = \mathbf{318.32 \text{ kN}}$$

Bearing Capacity of a Single Column

The unit weight of a jet grouting column is calculated as the weighted average of the unit weights of the mixtures in the interacting soil layers.

$$\gamma_{c,av} = \frac{\sum_{i=1}^7 \gamma_{mix,i} \times L_{e,i}}{L_p} = \frac{22 \times 4.35 + 22 \times 1.3 + 22 \times 9.5 + 22 \times 1.85}{17} = 22 \text{ kN/m}^3$$

$$W_p = \gamma_{c,av} L_p A_b = 22 \times 17 \times 0.28 = 105.75 \text{ kN}$$

Pore water pressure at the tip of the rigid column:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ + (20 - 10.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766 \text{ kN/m}^2$$

The net self-weight of the column is determined by taking into account the pore water pressure at the column tip.

$$W_{p,net} = W_p - u_w \times A_b = 105.75 - 192.77 \times 0.28 = 51.77 \text{ kN}$$

Bearing capacity was obtained by applying Equation (62).

$$R_{c;k} = R_{s;k} + R_{b;k} - W_p = 2246.35 + 318.32 - 51.77 = \mathbf{2512.9 \text{ kN}}$$

Design of a Single Column

Design axial load on the rigid column:: $F_{c;d} = 1081.27 \text{ kN}$

Partial factors: $\gamma_s = 1.5$ $\gamma_b = 2$

Design bearing capacity:

$$R_{c;d} = \frac{R_{s;k}}{\gamma_{Rs}} + \frac{R_{b;k}}{\gamma_{Ru}} = \frac{2246.35}{1.5} + \frac{318.32}{2} = \mathbf{1656.73 \text{ kN}}$$

$$F_{c;d} = 1081.27 \text{ kN/m}^2 \leq R_{c;d} = 1656.73 \text{ kN/m}^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{R_{c;k}}{F_{c;d}} = \frac{2512.9}{1081.27} = 2.32$$

Bearing Capacity of Rigid Column Group

The bearing capacity of the rigid column group was calculated using the Terzaghi block method.

Block Shaft Resistance

Shaft resistance is calculated individually for each soil layer interacting with the column, and their sum gives the total shaft resistance of the block.

- **Interacting Layer 1: [-4.85m] ↔ [-9.2m]**

Soil: Silty Clay (Alluvium)

Effective column length in block/soil interaction zone $L_e = 4.35 \text{ m}$

$$\gamma_{sat} = 17.9 \text{ kN/m}^3 \quad \gamma_n = 17 \text{ kN/m}^3 \quad \gamma_w = 9.81 \text{ kN/m}^3 \quad \gamma' = 8.1 \text{ kN/m}^3$$

$$c' = 4 \text{ kPa} \quad \phi' = 24^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 24) \times 3^{0,5} \times \tan 24 = 0.46$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (7.025 - 4.5) \times 17.9 = 130.518 \text{ kN/m}^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (7.025 - 4.5) \times 9.81 = 47.333 \text{ kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (7.025 - 4.5) \times 8.1 = 83.232 \text{ kN/m}^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 4 + 0.46 \times 83.23 = 42.08 \text{ kN/m}^2$$

Block perimeter $\xi = 100 \text{ m}$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 100 \times 4.35 = 435 \text{ m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 42.08 \times 435 = 18304.31 \text{ kN}$$

- **Interacting Layer 2: [-9.2m] ↔ [-10.5m]**

Soil: Gravelly Clayey Sand

Effective column length in block/soil interaction zone $L_e = 1.3 \text{ m}$

$$\gamma_{sat} = 19.3 \text{ kN/m}^3 \quad \gamma_n = 17.5 \text{ kN/m}^3 \quad \gamma_w = 9.81 \text{ kN/m}^3 \quad \gamma' = 9.5 \text{ kN/m}^3$$

$$c' = 1 \text{ kPa} \quad \phi' = 28^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 28) \times 3^{0,5} \times \tan 28 = 0.49$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 \\ + (9.2 - 4.5) \times 17.9 + (9.85 - 9.2) \times 19.3 = 181.995 \text{ kN/m}^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (9.85 - 9.2) \times 9.81 = 75.046 \text{ kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 \\ + (9.2 - 4.5) \times 8.1 + (9.85 - 9.2) \times 9.5 = 107.025 \text{ kN/m}^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 1 + 0.49 \times 107.02 = 53.29 \text{ kN/m}^2$$

Block perimeter $\xi = 100 \text{ m}$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 100 \times 1.3 = 130 \text{ m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 53.29 \times 130 = 6927.86 \text{ kN}$$

- **Interacting Layer 3: [-10.5m] ↔ [-20m]**

Soil: Clay (Sandy Clay with Silt – SaClSi)

Effective column length in block/soil interaction zone $L_e = 9.5 \text{ m}$

$$\gamma_{sat} = 19.5 \text{ kN/m}^3 \quad \gamma_n = 18.7 \text{ kN/m}^3 \quad \gamma_w = 9.81 \text{ kN/m}^3 \quad \gamma' = 9.7 \text{ kN/m}^3$$

$$c' = 12 \text{ kPa} \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 \\ + (10.5 - 9.2) \times 19.3 + (15.25 - 10.5) \times 19.5 = 287.165 \text{ kN/m}^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 \\ + (10.5 - 9.2) \times 9.81 + (15.25 - 10.5) \times 9.81 = 128.02 \text{ kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 \\ + (10.5 - 9.2) \times 9.5 + (15.25 - 10.5) \times 9.7 = 159.275 \text{ kN/m}^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 12 + 0.41 \times 159.28 = 78.07 \text{ kN/m}^2$$

Block perimeter $\xi = 100 \text{ m}$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 100 \times 9.5 = 950 \text{ m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 78.07 \times 950 = 74163.94 \text{ kN}$$

- **Interacting Layer 4: [-20m] ↔ [-21.85m]**

Soil: Clay 2 (Sandy Clay – SaCl)

Effective column length in block/soil interaction zone $L_e = 1.85 \text{ m}$

$$\gamma_{sat} = 19.5 \text{ kN/m}^3 \quad \gamma_n = 18.7 \text{ kN/m}^3 \quad \gamma_w = 9.81 \text{ kN/m}^3 \quad \gamma' = 9.7 \text{ kN/m}^3$$

$$c' = 18 \text{ kPa} \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 + (10.5 - 9.2) \times 19.3 + (20 - 10.5) \times 19.5 + (20.925 - 20) \times 19.5 = 397.828 \text{ kN/m}^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 + (20 - 10.5) \times 9.81 + (20.925 - 20) \times 9.81 = 183.692 \text{ kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 + (10.5 - 9.2) \times 9.5 + (20 - 10.5) \times 9.7 + (20.925 - 20) \times 9.7 = 214.322 \text{ kN/m}^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 18 + 0.41 \times 214.32 = 106.9 \text{ kN/m}^2$$

Block perimeter $\xi = 100 \text{ m}$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 100 \times 1.85 = 185 \text{ m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 106.9 \times 185 = 19776.69 \text{ kN}$$

• Total Shaft Resistance

Shaft resistances of all block/soil interaction layers are summed.

$$R_{s;k,gr} = \sum_{i=1}^4 Q_{si} = 18304.31 + 6927.86 + 74163.94 + 19776.69 = \mathbf{119172.8 \text{ kN}}$$

Block Base Resistance

Effective shear strength angle at the block base: $\phi' = 20^\circ$

Elevation at the block base = -21.85m

Natural stresses at the block base have been calculated.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (20 - 10.5) \times 19.5 + (21.85 - 20) \times 19.5 = 415.865 kN/m^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ + (20 - 10.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766 kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (20 - 10.5) \times 9.7 + (21.85 - 20) \times 9.7 = 223.295 kN/m^2$$

Plastification angle $\psi_p = 0.4\pi$

Block base resistance was calculated for effective stresses using Equations (81), (82), and (83).

$$N_t = \left(\tan 20 + \sqrt{1 + \tan^2 20} \right)^2 e^{2 \times 0.4\pi \times \tan 20} = 5.091$$

$$f_b = 5.091 \times 223.3 = 1136.82 kN/m^2$$

Block base area:

$$A_b = 600 m^2$$

Base resistance:

$$R_{b;k,gr} = 1136.82 \times 600 = \mathbf{682103.92 kN}$$

Block Bearing Capacity

Self-weight of the rigid columns within the block:

$$W_{p,b} = n_p \times W_p = 176 \times 105.75 = 18611.3 kN$$

Area of the soil enclosed within the block:

$$A_s = A_b - n_p \times \left(\frac{\pi \times D^2}{4} \right) = 600 - 176 \times \left(\frac{\pi \times 0.6^2}{4} \right) = 550.24 m^2$$

Self-weight of the soil enclosed within the block:

$$W_{s,b} = \sum_1^{10} \gamma_{n,i} L_{e,i} A_s = \\ 17 \times 4.35 \times 550.24 + 17.5 \times 1.3 \times 550.24 + 18.7 \times 9.5 \times 550.24 + 18.7 \times 1.85 \times 550.24 + = 354471.69 kN$$

Self-weight of the block:

$$W_b = W_{p,b} + W_{s,b} = 18611.3 + 354471.69 = 188604.3 kN$$

Pore water pressure at the block base:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ + (20 - 10.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766 kN/m^2$$

The net self-weight of the block is determined by taking into account the pore water pressure at the base.

$$W_{b,net} = W_b - u_w \times A_b = 188604.3 - 192.77 \times 600 = 72944.41 kN$$

Bearing capacity was obtained by applying Equation (62).

$$R_{c;k,gr} = R_{s;k,gr} + R_{b;k,gr} - W_b = 119172.8 + 682103.92 - 72944.41 = \mathbf{728332.31 kN}$$

The group efficiency has been limited to 1 in order to remain on the safe side.

$$R_{c;k,gr} = n \times R_{c;k} = 176 \times 2512.9 = 442270.16 kN$$

Design of Rigid Column Group

Axial design load on the rigid column group: $F_{c;d,gr} = 170000 kN$

Partial factor $\gamma_R = 1.5$

Design group bearing capacity:

$$R_{c;d,gr} = \frac{R_{c;k,gr}}{\gamma_R} = \frac{442270.16}{1.5} = \mathbf{294846.77 kN}$$

$$F_{c;d,gr} = 170000 kN/m^2 \leq R_{c;d} = 294846.77 kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{R_{c;k,gr}}{F_{c;d,gr}} = \frac{442270.16}{170000} = 2.6$$

9 “BLOCK D” Combined Bearing Capacity

The combined bearing capacity of the foundation system resting on rigid columns is being evaluated. The total capacity is obtained by combining the previously calculated shallow foundation bearing capacity with the bearing capacity of the rigid column group.

Combined bearing capacity:

$$q_{ult,comb} = q_{ult} + \frac{R_{c;k,gr}}{A} = 1826.95 + \frac{442270.16}{600} = \mathbf{2564.06 kN/m^2}$$

Design combined bearing capacity:

$$q_{t,comb} = q_t + \frac{R_{c;d,gr}}{A} = 1304.96 + \frac{294846.77}{600} = \mathbf{1796.37 kN/m^2}$$

10 “BLOCK C” Bearing Capacity of Shallow Foundation

The bearing capacity has been calculated using the Vesic method for effective stress analysis.

Foundation Geometry and Base Pressure

$B = 20m$ $L = 32.5m$ $D_f = 4.85m$ $q_0 = 300kN/m^2$ $P = 170000kN$ Foundation base elevation=-4.85m

Soil Profile

fill: [-0m]-[-4.5m]

$$\gamma_n = 18.5kN/m^3$$

$$\gamma_{sat} = 19.4kN/m^3$$

Effective cohesion $c' = 0kN/m^2$

Internal friction angle for effective stress $\phi' = 26^\circ$

Silty Clay (Alluvium): [-4.5m]-[-9.2m]

$$\gamma_n = 17kN/m^3$$

$$\gamma_{sat} = 17.9kN/m^3$$

Effective cohesion $c' = 4kN/m^2$

Internal friction angle for effective stress $\phi' = 24^\circ$

Gravelly Clayey Sand: [-9.2m]-[-10.5m]

$$\gamma_n = 17.5kN/m^3$$

$$\gamma_{sat} = 19.3kN/m^3$$

Effective cohesion $c' = 1kN/m^2$

Internal friction angle for effective stress $\phi' = 28^\circ$

Clay (Sandy Clay with Silt – SaClSi): [-10.5m]-[-20m]

$$\gamma_n = 18.7kN/m^3$$

$$\gamma_{sat} = 19.5kN/m^3$$

Effective cohesion $c' = 12kN/m^2$

Internal friction angle for effective stress $\phi' = 20^\circ$

Clay 2 (Sandy Clay – SaCl): [-20m]-[-40m]

$$\gamma_n = 18.7kN/m^3$$

$$\gamma_{sat} = 19.5kN/m^3$$

Effective cohesion $c' = 18kN/m^2$

Internal friction angle for effective stress $\phi' = 20^\circ$

Ground Water Table

$GWT = -2.2m$

Natural Stress Calculation at Foundation Base Level

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (4.85 - 4.5) \times 17.9 = 91.585kN/m^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (4.85 - 4.5) \times 9.81 = 25.996kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (4.85 - 4.5) \times 8.1 = 65.615kN/m^2$$

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The effective foundation dimensions are determined using Equations (6) and (7):

$$B' = 20m$$

$$L' = 32.5m$$

Geotechnical Parameters and Groundwater Table (GWT) Effect

The unit weight of the soil above the foundation base is $\gamma = 13.529kN/m^3$

The effective angle of internal friction of the soil above the foundation base is

$$\phi' = 25.86^\circ = 0.144\pi$$

The weighted average of the effective cohesion of the soil below the foundation base is

$$c' = 11kPa$$

The weighted average of the effective angle of internal friction of the soil below the foundation base is $\phi' = 21.39^\circ = 0.119\pi$

Effect of Groundwater Table

The groundwater effect on γ in the third term has been considered.

For $0 < Y_{ASS} \leq D_f$, the submerged unit weight γ is used. The weighted average submerged unit weight of the soil below the foundation base is $\gamma = 9.339kN/m^3$

Bearing Capacity Factors

The values of N_c , N_q , and N_γ were determined based on Equations (22), (23), and (40).

$$N_q^* = e^{\pi \tan 21.39} \tan^2 \left(45 + \frac{21.39}{2} \right) = 7.35$$

$$N_c = (7.35 - 1) \cot 21.39 = 16.22$$

$$N_q = e^{\pi \tan 25.86} \tan^2 \left(45 + \frac{25.86}{2} \right) = 11.67$$

$$N_\gamma = 2(7.35 + 1) \tan 21.39 = 6.54$$

Shape Factors

The shape factors were calculated using Equations (41), (42), and (43).

$$s_c = 1 + \frac{11.67}{16.22} \cdot \frac{20}{32.5} = 1.44$$

$$s_q = 1 + \frac{20}{32.5} \tan 25.86 = 1.3$$

$$s_\gamma = \max \left(1 - 0.4 \times \frac{20}{32.5} = 0.75; 0.6 \right) = 0.75$$

Depth Factors

Based on the calculations performed according to Equations (45), (46), (47) and (48):

$$\frac{4.85}{20} \leq 1 \rightarrow k = \frac{4.85}{20} = 0.2425$$

$$d_c = 1 + 0.4 \times 0.24 = 1.1$$

$$d_q = 1 + 2 \times \tan 25.86 \times (1 - \sin 25.86)^2 \times 0.24 = 1.07$$

$$d_\gamma = 1$$

Inclination Factors

Since there is no load inclination, the value of these factors is equal to 1.

$$i_q = 1$$

$$i_c = 1$$

$$i_\gamma = 1$$

Ground Factors (base on a slope)

Since there is no ground slope ($\beta = 0$), the value of these factors is equal to 1.

$$g_c = 1$$

$$g_q = 1$$

$$g_\gamma = 1$$

Base Factors (tilted base)

Taban eğimi olmadığı için ($\eta = 0$) bu faktörlerin değeri 1'e eşittir.

$$b_c = 1$$

$$b_q = 1$$

$$b_\gamma = 1$$

Bearing Capacity

$$c' = 11kPa$$

$$\phi' = 25.86^\circ (\text{for soil above the foundation base})$$

$$\phi' = 21.39^\circ (\text{for soil below the foundation base})$$

$$q = 65.61kN/m^2$$

$$N_c = 16.22 \quad N_q = 11.67 \quad N_\gamma = 6.54$$

$$s_c = 1.44 \quad s_q = 1.3 \quad s_\gamma = 0.75$$

$$d_c = 1.1 \quad d_q = 1.07 \quad d_\gamma = 1$$

$$i_c = 1 \quad i_q = 1 \quad i_\gamma = 1$$

$$g_c = 1 \quad g_q = 1 \quad g_\gamma = 1$$

$$b_c = 1 \quad b_q = 1 \quad b_\gamma = 1$$

$$B = 20m \quad B' = 20m \quad \gamma = 9.339kN/m^3$$

Based on effective stresses, the Vesic bearing capacity according to Equation (38):

$$q_{ult} = cN_c s_c d_c i_c g_c b_c + qN_q s_q d_q i_q g_q b_q + 0.5\gamma B N_\gamma s_\gamma d_\gamma i_\gamma g_\gamma b_\gamma$$

$$\begin{aligned} q_{ult} &= 11 \times 16.22 \times 1.44 \times 1.1 \times 1 \times 1 \times 1 \\ &\quad + 65.61 \times 11.67 \times 1.3 \times 1.07 \times 1 \times 1 \times 1 \\ &\quad + 0.5 \times 9.339 \times 20 \times 6.54 \times 0.75 \times 1 \times 1 \times 1 \times 1 \\ &= 1811.8kN/m^2 \end{aligned}$$

Design

$$\text{Contact Pressure } q_0 = 300kN/m^2$$

Partial factor $\gamma_{R,v} = 1.4$

Design bearing capacity (based on effective stresses):

$$q_t = \frac{q_{ult}}{\gamma_{R,v}} = \frac{1811.8}{1.4} = 1294.14kN$$

$$q_0 = 300kN/m^2 \leq q_t = 1294.14kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{q_{ult}}{q_0} = \frac{1811.8}{300} = 6.04$$

11 Bearing Capacity of “BLOCK C” Deep Foundation

Rigid column type: Jet grouting

Number of rigid columns= 187

Diameter of rigid column D= 60cm

Length of rigid column L= 17m

Rigid Column Cap

Geometry: Polygon

Coordinates of the rigid column cap: Polygon1: p1(X= 77.5276m Y= 62.3346m) ; p2(X= 85.0819m Y= 80.961m) ; p3(X= 115.1992m Y= 68.7463m) ; p4(X= 107.6449m Y= 50.1199m) ;

Shaft Resistance of a Single Column

Shaft resistance is calculated individually for each soil layer interacting with the column, and their sum gives the total shaft resistance of the column.

- **Interacting Layer 1: [-4.85m] ↔ [-9.2m]**

Soil: Silty Clay (Alluvium)

Effective column length in rigid column/soil interaction zone $L_e = 4.35m$

$$\gamma_{sat} = 17.9kN/m^3 \quad \gamma_n = 17kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 8.1kN/m^3$$

$$c' = 4kPa \quad \phi' = 24^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 24) \times 3^{0.5} \times \tan 24 = 0.46$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (7.025 - 4.5) \times 17.9 = 130.518 \text{ kN/m}^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (7.025 - 4.5) \times 9.81 = 47.333 \text{ kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (7.025 - 4.5) \times 8.1 = 83.232 \text{ kN/m}^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 4 + 0.46 \times 83.23 = 42.08 \text{ kN/m}^2$$

Lateral surface area of the rigid column:

$$A_s = \pi D L_e = \pi \times 0.6 \times 4.35 = 8.2 \text{ m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 42.08 \times 8.2 = 345.03 \text{ kN}$$

- **Interacting Layer 2: [-9.2m] ↔ [-10.5m]**

Soil: Gravelly Clayey Sand

Effective column length in rigid column/soil interaction zone $L_e = 1.3 \text{ m}$

$$\gamma_{sat} = 19.3 \text{ kN/m}^3 \quad \gamma_n = 17.5 \text{ kN/m}^3 \quad \gamma_w = 9.81 \text{ kN/m}^3 \quad \gamma' = 9.5 \text{ kN/m}^3$$

$$c' = 1 \text{ kPa} \quad \phi' = 28^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 28) \times 3^{0.5} \times \tan 28 = 0.49$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 \\ + (9.2 - 4.5) \times 17.9 + (9.85 - 9.2) \times 19.3 = 181.995 kN/m^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (9.85 - 9.2) \times 9.81 = 75.046 kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 \\ + (9.2 - 4.5) \times 8.1 + (9.85 - 9.2) \times 9.5 = 107.025 kN/m^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 1 + 0.49 \times 107.02 = 53.29 kN/m^2$$

Lateral surface area of the rigid column:

$$A_s = \pi D L_e = \pi \times 0.6 \times 1.3 = 2.45 m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 53.29 \times 2.45 = 130.59 kN$$

• Interacting Layer 3: [-10.5m] ↔ [-20m]

Soil: Clay (Sandy Clay with Silt – SaClSi)

Effective column length in rigid column/soil interaction zone $L_e = 9.5m$

$$\gamma_{sat} = 19.5 kN/m^3 \quad \gamma_n = 18.7 kN/m^3 \quad \gamma_w = 9.81 kN/m^3 \quad \gamma' = 9.7 kN/m^3$$

$$c' = 12 kPa \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 \\ + (10.5 - 9.2) \times 19.3 + (15.25 - 10.5) \times 19.5 = 287.165 kN/m^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 \\ + (10.5 - 9.2) \times 9.81 + (15.25 - 10.5) \times 9.81 = 128.02 kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 \\ + (10.5 - 9.2) \times 9.5 + (15.25 - 10.5) \times 9.7 = 159.275 kN/m^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 12 + 0.41 \times 159.28 = 78.07 kN/m^2$$

Lateral surface area of the rigid column:

$$A_s = \pi D L_e = \pi \times 0.6 \times 9.5 = 17.91 m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 78.07 \times 17.91 = 1397.96 kN$$

- **Interacting Layer 4: [-20m] ↔ [-21.85m]**

Soil: Clay 2 (Sandy Clay – SaCl)

Effective column length in rigid column/soil interaction zone $L_e = 1.85m$

$$\gamma_{sat} = 19.5 kN/m^3 \quad \gamma_n = 18.7 kN/m^3 \quad \gamma_w = 9.81 kN/m^3 \quad \gamma' = 9.7 kN/m^3$$

$$c' = 18 kPa \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (20 - 10.5) \times 19.5 + (20.925 - 20) \times 19.5 = 397.828 kN/m^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ + (20 - 10.5) \times 9.81 + (20.925 - 20) \times 9.81 = 183.692 kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (20 - 10.5) \times 9.7 + (20.925 - 20) \times 9.7 = 214.322 kN/m^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 18 + 0.41 \times 214.32 = 106.9 kN/m^2$$

Lateral surface area of the rigid column:

$$A_s = \pi D L_e = \pi \times 0.6 \times 1.85 = 3.49 m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 106.9 \times 3.49 = 372.78 kN$$

• Total Shaft Resistance

Shaft resistances of all rigid column/soil interaction layers are summed.

$$R_{s;k} = \sum_{i=1}^4 Q_{si} = 345.03 + 130.59 + 1397.96 + 372.78 = \mathbf{2246.35 kN}$$

Tip Resistance of a Single Column

Effective shear strength angle at the column tip: $\phi' = 20^\circ$

Tip elevation of the rigid column = -21.85m

Natural stresses at the tip of the rigid column have been calculated.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (20 - 10.5) \times 19.5 + (21.85 - 20) \times 19.5 = 415.865 kN/m^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ + (20 - 10.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766 kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (20 - 10.5) \times 9.7 + (21.85 - 20) \times 9.7 = 223.295 kN/m^2$$

Plastification angle $\psi_p = 0.4\pi$

Tip resistance was calculated for effective stresses using Equations (81), (82), and (83).

$$N_t = \left(\tan 20 + \sqrt{1 + \tan^2 20} \right)^2 e^{2 \times 0.4\pi \times \tan 20} = 5.091$$

$$f_b = 5.091 \times 223.3 = 1136.82 kN/m^2$$

Cross-sectional area of the rigid column:

$$A_b = \frac{\pi D^2}{4} = \frac{\pi \times 0.6^2}{4} = 0.28 m^2$$

Tip resistance:

$$R_{b;k} = 1136.82 \times 0.28 = \mathbf{318.32 kN}$$

Bearing Capacity of a Single Column

The unit weight of a jet grouting column is calculated as the weighted average of the unit weights of the mixtures in the interacting soil layers.

$$\gamma_{c,av} = \frac{\sum_{i=1}^7 \gamma_{mix,i} \times L_{e,i}}{L_p} = \frac{22 \times 4.35 + 22 \times 1.3 + 22 \times 9.5 + 22 \times 1.85}{17} = 22 kN/m^3$$

$$W_p = \gamma_{c,av} L_p A_b = 22 \times 17 \times 0.28 = 105.75 kN$$

Pore water pressure at the tip of the rigid column:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ + (20 - 10.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766 kN/m^2$$

The net self-weight of the column is determined by taking into account the pore water pressure at the column tip.

$$W_{p,net} = W_p - u_w \times A_b = 105.75 - 192.77 \times 0.28 = 51.77 kN$$

Bearing capacity was obtained by applying Equation (62).

$$R_{c;k} = R_{s;k} + R_{b;k} - W_p = 2246.35 + 318.32 - 51.77 = \mathbf{2512.9 kN}$$

Design of a Single Column

Design axial load on the rigid column:: $F_{c;d} = 1024.45 kN$

Partial factors: $\gamma_s = 1.5$ $\gamma_b = 2$

Design bearing capacity:

$$R_{c;d} = \frac{R_{s;k}}{\gamma_{Rs}} + \frac{R_{b;k}}{\gamma_{Ru}} = \frac{2246.35}{1.5} + \frac{318.32}{2} = \mathbf{1656.73kN}$$

$$F_{c;d} = 1024.45kN/m^2 \leq R_{c;d} = 1656.73kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{R_{c;k}}{F_{c;d}} = \frac{2512.9}{1024.45} = 2.45$$

Bearing Capacity of Rigid Column Group

The bearing capacity of the rigid column group was calculated using the Terzaghi block method.

Block Shaft Resistance

Shaft resistance is calculated individually for each soil layer interacting with the column, and their sum gives the total shaft resistance of the block.

- **Interacting Layer 1: [-4.85m] ↔ [-9.2m]**

Soil: Silty Clay (Alluvium)

Effective column length in block/soil interaction zone $L_e = 4.35m$

$$\gamma_{sat} = 17.9kN/m^3 \quad \gamma_n = 17kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 8.1kN/m^3$$

$$c' = 4kPa \quad \phi' = 24^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 24) \times 3^{0.5} \times \tan 24 = 0.46$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (7.025 - 4.5) \times 17.9 = 130.518kN/m^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (7.025 - 4.5) \times 9.81 = 47.333kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (7.025 - 4.5) \times 8.1 = 83.232 \text{ kN/m}^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 4 + 0.46 \times 83.23 = 42.08 \text{ kN/m}^2$$

Block perimeter $\xi = 105.2 \text{ m}$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 105.2 \times 4.35 = 457.62 \text{ m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 42.08 \times 457.62 = 19256.15 \text{ kN}$$

- **Interacting Layer 2: [-9.2m] ↔ [-10.5m]**

Soil: Gravelly Clayey Sand

Effective column length in block/soil interaction zone $L_e = 1.3 \text{ m}$

$$\gamma_{sat} = 19.3 \text{ kN/m}^3 \quad \gamma_n = 17.5 \text{ kN/m}^3 \quad \gamma_w = 9.81 \text{ kN/m}^3 \quad \gamma' = 9.5 \text{ kN/m}^3$$

$$c' = 1 \text{ kPa} \quad \phi' = 28^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 28) \times 3^{0.5} \times \tan 28 = 0.49$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma &= +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 \\ &+ (9.2 - 4.5) \times 17.9 + (9.85 - 9.2) \times 19.3 = 181.995 \text{ kN/m}^2 \end{aligned}$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (9.85 - 9.2) \times 9.81 = 75.046 \text{ kN/m}^2$$

Effective stress:

$$\begin{aligned} \sigma' &= +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 \\ &+ (9.2 - 4.5) \times 8.1 + (9.85 - 9.2) \times 9.5 = 107.025 \text{ kN/m}^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 1 + 0.49 \times 107.02 = 53.29kN/m^2$$

Block perimeter $\xi = 105.2m$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 105.2 \times 1.3 = 136.76m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 53.29 \times 136.76 = 7288.11kN$$

• **Interacting Layer 3: [-10.5m] ↔ [-20m]**

Soil: Clay (Sandy Clay with Silt – SaClSi)

Effective column length in block/soil interaction zone $L_e = 9.5m$

$$\gamma_{sat} = 19.5kN/m^3 \quad \gamma_n = 18.7kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 9.7kN/m^3$$

$$c' = 12kPa \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma = & +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 \\ & + (10.5 - 9.2) \times 19.3 + (15.25 - 10.5) \times 19.5 = 287.165kN/m^2 \end{aligned}$$

Pore water pressure:

$$\begin{aligned} u_w = & +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 \\ & + (10.5 - 9.2) \times 9.81 + (15.25 - 10.5) \times 9.81 = 128.02kN/m^2 \end{aligned}$$

Effective stress:

$$\begin{aligned} \sigma' = & +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 \\ & + (10.5 - 9.2) \times 9.5 + (15.25 - 10.5) \times 9.7 = 159.275kN/m^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 12 + 0.41 \times 159.28 = 78.07kN/m^2$$

Block perimeter $\xi = 105.2m$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 105.2 \times 9.5 = 999.4m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 78.07 \times 999.4 = 78020.51kN$$

• **Interacting Layer 4: [-20m] ↔ [-21.85m]**

Soil: Clay 2 (Sandy Clay – SaCl)

Effective column length in block/soil interaction zone $L_e = 1.85m$

$$\gamma_{sat} = 19.5kN/m^3 \quad \gamma_n = 18.7kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 9.7kN/m^3$$

$$c' = 18kPa \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (20 - 10.5) \times 19.5 + (20.925 - 20) \times 19.5 = 397.828kN/m^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ + (20 - 10.5) \times 9.81 + (20.925 - 20) \times 9.81 = 183.692kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (20 - 10.5) \times 9.7 + (20.925 - 20) \times 9.7 = 214.322kN/m^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 18 + 0.41 \times 214.32 = 106.9kN/m^2$$

Block perimeter $\xi = 105.2m$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 105.2 \times 1.85 = 194.62m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 106.9 \times 194.62 = 20805.09kN$$

• Total Shaft Resistance

Shaft resistances of all block/soil interaction layers are summed.

$$R_{s;k,gr} = \sum_{i=1}^4 Q_{si} = 19256.15 + 7288.11 + 78020.51 + 20805.09 = \mathbf{125369.85kN}$$

Block Base Resistance

Effective shear strength angle at the block base: $\phi' = 20^\circ$

Elevation at the block base = -21.85m

Natural stresses at the block base have been calculated.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 19.4 + (9.2 - 4.5) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (20 - 10.5) \times 19.5 + (21.85 - 20) \times 19.5 = 415.865kN/m^2$$

Pore water pressure:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ + (20 - 10.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (4.5 - 2.2) \times 9.6 + (9.2 - 4.5) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (20 - 10.5) \times 9.7 + (21.85 - 20) \times 9.7 = 223.295kN/m^2$$

Plastification angle $\psi_p = 0.4\pi$

Block base resistance was calculated for effective stresses using Equations (81), (82), and (83).

$$N_t = \left(\tan 20 + \sqrt{1 + \tan^2 20} \right)^2 e^{2 \times 0.4\pi \times \tan 20} = 5.091$$

$$f_b = 5.091 \times 223.3 = 1136.82kN/m^2$$

Block base area:

$$A_b = 653.25m^2$$

Base resistance:

$$R_{b;k,gr} = 1136.82 \times 653.25 = \mathbf{742641.16kN}$$

Block Bearing Capacity

Self-weight of the rigid columns within the block:

$$W_{p,b} = n_p \times W_p = 187 \times 105.75 = 19774.5kN$$

Area of the soil enclosed within the block:

$$A_s = A_b - n_p \times \left(\frac{\pi \times D^2}{4} \right) = 653.25 - 187 \times \left(\frac{\pi \times 0.6^2}{4} \right) = 600.38m^2$$

Self-weight of the soil enclosed within the block:

$$W_{s,b} = \sum_1^{10} \gamma_{n,i} L_{e,i} A_s = 17 \times 4.35 \times 600.38 + 17.5 \times 1.3 \times 600.38 + 18.7 \times 9.5 \times 600.38 + 18.7 \times 1.85 \times 600.38 + = 539955.27kN$$

Self-weight of the block:

$$W_b = W_{p,b} + W_{s,b} = 19774.5 + 539955.27 = 205258.09kN$$

Pore water pressure at the block base:

$$u_w = +(4.5 - 2.2) \times 9.81 + (9.2 - 4.5) \times 9.81 + (10.5 - 9.2) \times 9.81 + (20 - 10.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766kN/m^2$$

The net self-weight of the block is determined by taking into account the pore water pressure at the base.

$$W_{b,net} = W_b - u_w \times A_b = 205258.09 - 192.77 \times 653.25 = 79333.3kN$$

Bearing capacity was obtained by applying Equation (62).

$$R_{c;k,gr} = R_{s;k,gr} + R_{b;k,gr} - W_b = 125369.85 + 742641.16 - 79333.3 = \mathbf{788677.7kN}$$

The group efficiency has been limited to 1 in order to remain on the safe side.

$$R_{c;k,gr} = n \times R_{c;k} = 187 \times 2512.9 = 469912.05kN$$

Design of Rigid Column Group

Axial design load on the rigid column group: $F_{c;d,gr} = 170000kN$

Partial factor $\gamma_R = 1.5$

Design group bearing capacity:

$$R_{c;d,gr} = \frac{R_{c;k,gr}}{\gamma_R} = \frac{469912.05}{1.5} = \mathbf{313274.7kN}$$

$$F_{c;d,gr} = 170000kN/m^2 \leq R_{c;d} = 313274.7kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{R_{c;k,gr}}{F_{c;d,gr}} = \frac{469912.05}{170000} = 2.76$$

12 “BLOCK C” Combined Bearing Capacity

The combined bearing capacity of the foundation system resting on rigid columns is being evaluated. The total capacity is obtained by combining the previously calculated shallow foundation bearing capacity with the bearing capacity of the rigid column group.

Combined bearing capacity:

$$q_{ult,comb} = q_{ult} + \frac{R_{c;k,gr}}{A} = 1811.8 + \frac{469912.05}{653.25} = \mathbf{2531.14kN/m^2}$$

Design combined bearing capacity:

$$q_{t,comb} = q_t + \frac{R_{c;d,gr}}{A} = 1294.14 + \frac{313274.7}{653.25} = \mathbf{1773.71kN/m^2}$$

13 “BLOCK A” Bearing Capacity of Shallow Foundation

The bearing capacity has been calculated using the Vesic method for effective stress analysis.

Foundation Geometry and Base Pressure

$B = 19.5m$ $L = 32m$ $D_f = 4.85m$ $q_0 = 300kN/m^2$ $P = 170000kN$ Foundation base elevation=-4.85m

Soil Profile

Fill: [-0m]-[-2.8m]

$$\gamma_n = 18.5kN/m^3$$

$$\gamma_{sat} = 19.4kN/m^3$$

Effective cohesion $c' = 0kN/m^2$

Internal friction angle for effective stress $\phi' = 26^\circ$

Silty Clay (Alluvium): [-2.8m]-[-9.2m]

$$\gamma_n = 17kN/m^3$$

$$\gamma_{sat} = 17.9kN/m^3$$

Effective cohesion $c' = 4kN/m^2$

Internal friction angle for effective stress $\phi' = 24^\circ$

Gravelly Clayey Sand: [-9.2m]-[-10.5m]

$$\gamma_n = 17.5kN/m^3$$

$$\gamma_{sat} = 19.3kN/m^3$$

Effective cohesion $c' = 1kN/m^2$

Internal friction angle for effective stress $\phi' = 28^\circ$

Clay (Sandy Clay with Silt – SaClSi): [-10.5m]-[-16.5m]

$$\gamma_n = 18.7kN/m^3$$

$$\gamma_{sat} = 19.5kN/m^3$$

Effective cohesion $c' = 12kN/m^2$

Internal friction angle for effective stress $\phi' = 20^\circ$

sand: [-16.5m]-[-20m]

$$\gamma_n = 17.2kN/m^3$$

$$\gamma_{sat} = 18.3kN/m^3$$

Effective cohesion $c' = 1kN/m^2$

Internal friction angle for effective stress $\phi' = 30^\circ$

Clay 2 (Sandy Clay – SaCl): [-20m]-[-40m]

$$\gamma_n = 18.7kN/m^3$$

$$\gamma_{sat} = 19.5kN/m^3$$

Effective cohesion $c' = 18kN/m^2$

Internal friction angle for effective stress $\phi' = 20^\circ$

Ground Water Table

$$GWT = -2.2m$$

Natural Stress Calculation at Foundation Base Level

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (4.85 - 2.8) \times 17.9 = 89.035 \text{ kN/m}^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (4.85 - 2.8) \times 9.81 = 25.996 \text{ kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (4.85 - 2.8) \times 8.1 = 63.065 \text{ kN/m}^2$$

Eksantrite

The effective foundation dimensions are determined using Equations (6) and (7):

$$B' = 19.5 \text{ m}$$

$$L' = 32 \text{ m}$$

Geotechnical Parameters and Groundwater Table (GWT) Effect

The unit weight of the soil above the foundation base is $\gamma = 13.003 \text{ kN/m}^3$

The effective angle of internal friction of the soil above the foundation base is

$$\phi' = 25.15^\circ = 0.14\pi$$

The weighted average of the effective cohesion of the soil below the foundation base is

$$c' = 8.85 \text{ kPa}$$

The weighted average of the effective angle of internal friction of the soil below the foundation base is $\phi' = 23.22^\circ = 0.129\pi$

Effect of Groundwater Table

The groundwater effect on γ in the third term has been considered.

For $0 < Y_{ASS} \leq D_f$, the submerged unit weight γ is used. The weighted average submerged unit weight of the soil below the foundation base is $\gamma = 9.114 \text{ kN/m}^3$

Bearing Capacity Factors

The values of N_c , N_q , and N_γ were determined based on Equations (22), (23), and (40).

$$N_q^* = e^{\pi \tan 23.22} \tan^2 \left(45 + \frac{23.22}{2} \right) = 8.86$$

$$N_c = (8.86 - 1) \cot 23.22 = 18.32$$

$$N_q = e^{\pi \tan 25.15} \tan^2 \left(45 + \frac{25.15}{2} \right) = 10.84$$

$$N_\gamma = 2(8.86 + 1) \tan 23.22 = 8.46$$

Shape Factors

The shape factors were calculated using Equations (41), (42), and (43).

$$s_c = 1 + \frac{10.84}{18.32} \cdot \frac{19.5}{32} = 1.36$$

$$s_q = 1 + \frac{19.5}{32} \tan 25.15 = 1.29$$

$$s_\gamma = \max \left(1 - 0.4 \times \frac{19.5}{32} = 0.76; 0.6 \right) = 0.76$$

Depth Factors

Based on the calculations performed according to Equations (45), (46), (47) and (48):

$$\frac{4.85}{19.5} \leq 1 \rightarrow k = \frac{4.85}{19.5} = 0.2487179487179487$$

$$d_c = 1 + 0.4 \times 0.25 = 1.1$$

$$d_q = 1 + 2 \times \tan 25.15 \times (1 - \sin 25.15)^2 \times 0.25 = 1.08$$

$$d_\gamma = 1$$

Inclination Factors

Since there is no load inclination, the value of these factors is equal to 1.

$$i_q = 1$$

$$i_c = 1$$

$$i_\gamma = 1$$

Ground Factors (base on a slope)

Since there is no ground slope ($\beta = 0$), the value of these factors is equal to 1.

$$g_c = 1$$

$$g_q = 1$$

$$g_\gamma = 1$$

Base Factors (tilted base)

Taban eğimi olmadığı için ($\eta = 0$) bu faktörlerin değeri 1'e eşittir.

$$b_c = 1$$

$$b_q = 1$$

$$b_\gamma = 1$$

Bearing Capacity

$$c' = 8.85kPa$$

$$\phi' = 25.15^\circ (\text{for soil above the foundation base})$$

$$\phi' = 23.22^\circ (\text{for soil below the foundation base})$$

$$q = 63.06kN/m^2$$

$$N_c = 18.32 \quad N_q = 10.84 \quad N_\gamma = 8.46$$

$$s_c = 1.36 \quad s_q = 1.29 \quad s_\gamma = 0.76$$

$$d_c = 1.1 \quad d_q = 1.08 \quad d_\gamma = 1$$

$$i_c = 1 \quad i_q = 1 \quad i_\gamma = 1$$

$$g_c = 1 \quad g_q = 1 \quad g_\gamma = 1$$

$$b_c = 1 \quad b_q = 1 \quad b_\gamma = 1$$

$$B = 19.5m \quad B' = 19.5m \quad \gamma = 9.114kN/m^3$$

Based on effective stresses, the Vesic bearing capacity according to Equation (38):

$$q_{ult} = cN_c s_c d_c i_c g_c b_c + qN_q s_q d_q i_q g_q b_q + 0.5\gamma B N_\gamma s_\gamma d_\gamma i_\gamma g_\gamma b_\gamma$$

$$\begin{aligned} q_{ult} &= 8.85 \times 18.32 \times 1.36 \times 1.1 \times 1 \times 1 \times 1 \\ &\quad + 63.06 \times 10.84 \times 1.29 \times 1.08 \times 1 \times 1 \times 1 \\ &\quad + 0.5 \times 9.114 \times 19.5 \times 8.46 \times 0.76 \times 1 \times 1 \times 1 \times 1 \\ &= 1757.88kN/m^2 \end{aligned}$$

Design

$$\text{Contact Pressure } q_0 = 300kN/m^2$$

$$\text{Partial factor } \gamma_{R;v} = 1.4$$

Design bearing capacity (based on effective stresses):

$$q_t = \frac{q_{ult}}{\gamma_{R;v}} = \frac{1757.88}{1.4} = 1255.63kN$$

$$q_0 = 300kN/m^2 \leq q_t = 1255.63kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{q_{ult}}{q_0} = \frac{1757.88}{300} = 5.86$$

14 Bearing Capacity of “BLOCK A” Deep Foundation

Rigid column type: Jet grouting

Number of rigid columns= 191

Diameter of rigid column D= 60cm

Length of rigid column L= 17m

Rigid Column Cap

Geometry: Polygon

Coordinates of the rigid column cap: Polygon1: p1(X= 116.3176m Y= 22.6904m) ; p2(X= 116.3177m Y= 44.7456m) ; p3(X= 135.851m Y= 42.1904m) ; p4(X= 148.3176m Y= 42.14904m) ; p5(X= 148.3176m Y= 22.6904m) ;

Shaft Resistance of a Single Column

Shaft resistance is calculated individually for each soil layer interacting with the column, and their sum gives the total shaft resistance of the column.

- **Interacting Layer 1: [-4.85m] ↔ [-9.2m]**

Soil: Silty Clay (Alluvium))

Effective column length in rigid column/soil interaction zone $L_e = 4.35m$

$$\gamma_{sat} = 17.9kN/m^3 \quad \gamma_n = 17kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 8.1kN/m^3$$

$$c' = 4kPa \quad \phi' = 24^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 24) \times 3^{0.5} \times \tan 24 = 0.46$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (7.025 - 2.8) \times 17.9 = 127.968 \text{ kN/m}^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (7.025 - 2.8) \times 9.81 = 47.333 \text{ kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (7.025 - 2.8) \times 8.1 = 80.682 \text{ kN/m}^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 4 + 0.46 \times 80.68 = 40.91 \text{ kN/m}^2$$

Lateral surface area of the rigid column:

$$A_s = \pi D L_e = \pi \times 0.6 \times 4.35 = 8.2 \text{ m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 40.91 \times 8.2 = 335.46 \text{ kN}$$

• Interacting Layer 2: [-9.2m] ↔ [-10.5m]

Soil: Gravelly Clayey Sand

Effective column length in rigid column/soil interaction zone $L_e = 1.3 \text{ m}$

$$\gamma_{sat} = 19.3 \text{ kN/m}^3 \quad \gamma_n = 17.5 \text{ kN/m}^3 \quad \gamma_w = 9.81 \text{ kN/m}^3 \quad \gamma' = 9.5 \text{ kN/m}^3$$

$$c' = 1 \text{ kPa} \quad \phi' = 28^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 28) \times 3^{0.5} \times \tan 28 = 0.49$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 \\ &+ (9.2 - 2.8) \times 17.9 + (9.85 - 9.2) \times 19.3 = 179.445 \text{ kN/m}^2 \end{aligned}$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (9.85 - 9.2) \times 9.81 = 75.047 \text{ kN/m}^2$$

Effective stress:

$$\begin{aligned} \sigma' &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 \\ &+ (9.2 - 2.8) \times 8.1 + (9.85 - 9.2) \times 9.5 = 104.475 \text{ kN/m}^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 1 + 0.49 \times 104.47 = 52.05 \text{ kN/m}^2$$

Lateral surface area of the rigid column:

$$A_s = \pi D L_e = \pi \times 0.6 \times 1.3 = 2.45 \text{ m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 52.05 \times 2.45 = 127.53 \text{ kN}$$

- **Interacting Layer 3: [-10.5m] ↔ [-16.5m]**

Soil: Clay (Sandy Clay with Silt – SaClSi)

Effective column length in rigid column/soil interaction zone $L_e = 6\text{m}$

$$\gamma_{sat} = 19.5 \text{ kN/m}^3 \quad \gamma_n = 18.7 \text{ kN/m}^3 \quad \gamma_w = 9.81 \text{ kN/m}^3 \quad \gamma' = 9.7 \text{ kN/m}^3$$

$$c' = 12 \text{ kPa} \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 \\ &+ (10.5 - 9.2) \times 19.3 + (13.5 - 10.5) \times 19.5 = 250.49 \text{ kN/m}^2 \end{aligned}$$

Pore water pressure:

$$\begin{aligned} u_w &= +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 \\ &+ (10.5 - 9.2) \times 9.81 + (13.5 - 10.5) \times 9.81 = 110.853 \text{ kN/m}^2 \end{aligned}$$

Effective stress:

$$\begin{aligned}\sigma' &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 \\ &+ (10.5 - 9.2) \times 9.5 + (13.5 - 10.5) \times 9.7 = 139.75 \text{ kN/m}^2\end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 12 + 0.41 \times 139.75 = 69.97 \text{ kN/m}^2$$

Lateral surface area of the rigid column:

$$A_s = \pi D L_e = \pi \times 0.6 \times 6 = 11.31 \text{ m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 69.97 \times 11.31 = 791.32 \text{ kN}$$

- **Interacting Layer 4: [-16.5m] ↔ [-20m]**

Soil: sand

Effective column length in rigid column/soil interaction zone $L_e = 3.5 \text{ m}$

$$\gamma_{sat} = 18.3 \text{ kN/m}^3 \quad \gamma_n = 17.2 \text{ kN/m}^3 \quad \gamma_w = 9.81 \text{ kN/m}^3 \quad \gamma' = 8.5 \text{ kN/m}^3$$

$$c' = 1 \text{ kPa} \quad \phi' = 30^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 30) \times 3^{0.5} \times \tan 30 = 0.5$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned}\sigma &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ &+ (16.5 - 10.5) \times 19.5 + (18.25 - 16.5) \times 18.3 = 341.015 \text{ kN/m}^2\end{aligned}$$

Pore water pressure:

$$\begin{aligned}u_w &= +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ &+ (16.5 - 10.5) \times 9.81 + (18.25 - 16.5) \times 9.81 = 157.45 \text{ kN/m}^2\end{aligned}$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (16.5 - 10.5) \times 9.7 + (18.25 - 16.5) \times 8.5 = 183.725 kN/m^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 1 + 0.5 \times 183.72 = 92.86 kN/m^2$$

Lateral surface area of the rigid column:

$$A_s = \pi D L_e = \pi \times 0.6 \times 3.5 = 6.6 m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 92.86 \times 6.6 = 612.65 kN$$

- **Interacting Layer 5: [-20m] ↔ [-21.85m]**

Soil: Clay 2 (Sandy Clay – SaCl)

Effective column length in rigid column/soil interaction zone $L_e = 1.85m$

$$\gamma_{sat} = 19.5 kN/m^3 \quad \gamma_n = 18.7 kN/m^3 \quad \gamma_w = 9.81 kN/m^3 \quad \gamma' = 9.7 kN/m^3$$

$$c' = 18 kPa \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (16.5 - 10.5) \times 19.5 + (20 - 16.5) \times 18.3 + (20.925 - 20) \times 19.5 = 391.078 kN/m^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 + (16.5 - 10.5) \times 9.81 \\ + (20 - 16.5) \times 9.81 + (20.925 - 20) \times 9.81 = 183.692 kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (16.5 - 10.5) \times 9.7 + (20 - 16.5) \times 8.5 + (20.925 - 20) \times 9.7 = 207.572 \text{ kN/m}^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 18 + 0.41 \times 207.57 = 104.1 \text{ kN/m}^2$$

Lateral surface area of the rigid column:

$$A_s = \pi D L_e = \pi \times 0.6 \times 1.85 = 3.49 \text{ m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 104.1 \times 3.49 = 363.02 \text{ kN}$$

• Total Shaft Resistance

Shaft resistances of all rigid column/soil interaction layers are summed.

$$R_{s;k} = \sum_{i=1}^5 Q_{si} = 335.46 + 127.53 + 791.32 + 612.65 + 363.02 = \mathbf{2229.98 \text{ kN}}$$

Tip Resistance of a Single Column

Effective shear strength angle at the column tip: $\phi' = 20^\circ$

Tip elevation of the rigid column = -21.85m

Natural stresses at the tip of the rigid column have been calculated.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (16.5 - 10.5) \times 19.5 + (20 - 16.5) \times 18.3 + (21.85 - 20) \times 19.5 = 409.115 \text{ kN/m}^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 + (16.5 - 10.5) \times 9.81 \\ + (20 - 16.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766 \text{ kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (16.5 - 10.5) \times 9.7 + (20 - 16.5) \times 8.5 + (21.85 - 20) \times 9.7 = 216.545 \text{ kN/m}^2$$

Plastification angle $\psi_p = 0.4\pi$

Tip resistance was calculated for effective stresses using Equations (81), (82), and (83).

$$N_t = \left(\tan 20 + \sqrt{1 + \tan^2 20} \right)^2 e^{2 \times 0.4\pi \times \tan 20} = 5.091$$

$$f_b = 5.091 \times 216.54 = 1102.41 \text{ kN/m}^2$$

Cross-sectional area of the rigid column:

$$A_b = \frac{\pi D^2}{4} = \frac{\pi \times 0.6^2}{4} = 0.28 \text{ m}^2$$

Tip resistance:

$$R_{b;k} = 1102.41 \times 0.28 = \mathbf{308.69 \text{ kN}}$$

Bearing Capacity of a Single Column

The unit weight of a jet grouting column is calculated as the weighted average of the unit weights of the mixtures in the interacting soil layers.

$$\gamma_{c,av} = \frac{\sum_{i=1}^8 \gamma_{mix,i} \times L_{e,i}}{L_p} = \frac{22 \times 4.35 + 22 \times 1.3 + 22 \times 6 + 22 \times 3.5 + 22 \times 1.85}{17} = 22 \text{ kN/m}^3$$

$$W_p = \gamma_{c,av} L_p A_b = 22 \times 17 \times 0.28 = 105.75 \text{ kN}$$

Pore water pressure at the tip of the rigid column:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 + (16.5 - 10.5) \times 9.81 + (20 - 16.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766 \text{ kN/m}^2$$

The net self-weight of the column is determined by taking into account the pore water pressure at the column tip.

$$W_{p,net} = W_p - u_w \times A_b = 105.75 - 192.77 \times 0.28 = 51.77 \text{ kN}$$

Bearing capacity was obtained by applying Equation (62).

$$R_{c;k} = R_{s;k} + R_{b;k} - W_p = 2229.98 + 308.69 - 51.77 = \mathbf{2486.91 \text{ kN}}$$

Design of a Single Column

Design axial load on the rigid column:: $F_{c;d} = 1005.41 \text{ kN}$

Partial factors: $\gamma_s = 1.5$ $\gamma_b = 2$

Design bearing capacity:

$$R_{c;d} = \frac{R_{s;k}}{\gamma_{Rs}} + \frac{R_{b;k}}{\gamma_{Ru}} = \frac{2229.98}{1.5} + \frac{308.69}{2} = \mathbf{1641 \text{ kN}}$$

$$F_{c;d} = 1005.41kN/m^2 \leq R_{c;d} = 1641kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{R_{c;k}}{F_{c;d}} = \frac{2486.91}{1005.41} = 2.47$$

Bearing Capacity of Rigid Column Group

The bearing capacity of the rigid column group was calculated using the Terzaghi block method.

Block Shaft Resistance

Shaft resistance is calculated individually for each soil layer interacting with the column, and their sum gives the total shaft resistance of the block.

- **Interacting Layer 1: [-4.85m] ↔ [-9.2m]**

Soil: Silty Clay (Alluvium))

Effective column length in block/soil interaction zone $L_e = 4.35m$

$$\gamma_{sat} = 17.9kN/m^3 \quad \gamma_n = 17kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 8.1kN/m^3$$

$$c' = 4kPa \quad \phi' = 24^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 24) \times 3^{0.5} \times \tan 24 = 0.46$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (7.025 - 2.8) \times 17.9 = 127.968kN/m^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (7.025 - 2.8) \times 9.81 = 47.333kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (7.025 - 2.8) \times 8.1 = 80.682kN/m^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 4 + 0.46 \times 80.68 = 40.91kN/m^2$$

Block perimeter $\xi = 105.7m$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 105.7 \times 4.35 = 459.78m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 40.91 \times 459.78 = 18810.65kN$$

• **Interacting Layer 2: [-9.2m] ↔ [-10.5m]**

Soil: Gravelly Clayey Sand

Effective column length in block/soil interaction zone $L_e = 1.3m$

$$\gamma_{sat} = 19.3kN/m^3 \quad \gamma_n = 17.5kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 9.5kN/m^3$$

$$c' = 1kPa \quad \phi' = 28^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 28) \times 3^{0.5} \times \tan 28 = 0.49$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 \\ &+ (9.2 - 2.8) \times 17.9 + (9.85 - 9.2) \times 19.3 = 179.445kN/m^2 \end{aligned}$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (9.85 - 9.2) \times 9.81 = 75.047kN/m^2$$

Effective stress:

$$\begin{aligned} \sigma' &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 \\ &+ (9.2 - 2.8) \times 8.1 + (9.85 - 9.2) \times 9.5 = 104.475kN/m^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 1 + 0.49 \times 104.47 = 52.05kN/m^2$$

Block perimeter $\xi = 105.7m$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 105.7 \times 1.3 = 137.41m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 52.05 \times 137.41 = 7151.32kN$$

• **Interacting Layer 3: [-10.5m] ↔ [-16.5m]**

Soil: Clay (Sandy Clay with Silt – SaClSi)

Effective column length in block/soil interaction zone $L_e = 6m$

$$\gamma_{sat} = 19.5kN/m^3 \quad \gamma_n = 18.7kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 9.7kN/m^3$$

$$c' = 12kPa \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma = & +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 \\ & + (10.5 - 9.2) \times 19.3 + (13.5 - 10.5) \times 19.5 = 250.49kN/m^2 \end{aligned}$$

Pore water pressure:

$$\begin{aligned} u_w = & +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 \\ & + (10.5 - 9.2) \times 9.81 + (13.5 - 10.5) \times 9.81 = 110.853kN/m^2 \end{aligned}$$

Effective stress:

$$\begin{aligned} \sigma' = & +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 \\ & + (10.5 - 9.2) \times 9.5 + (13.5 - 10.5) \times 9.7 = 139.75kN/m^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 12 + 0.41 \times 139.75 = 69.97kN/m^2$$

Block perimeter $\xi = 105.7m$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 105.7 \times 6 = 634.18m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 69.97 \times 634.18 = 44372.51kN$$

• **Interacting Layer 4: [-16.5m] ↔ [-20m]**

Soil: sand

Effective column length in block/soil interaction zone $L_e = 3.5m$

$$\gamma_{sat} = 18.3kN/m^3 \quad \gamma_n = 17.2kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 8.5kN/m^3$$

$$c' = 1kPa \quad \phi' = 30^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 30) \times 3^{0.5} \times \tan 30 = 0.5$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (16.5 - 10.5) \times 19.5 + (18.25 - 16.5) \times 18.3 = 341.015kN/m^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ + (16.5 - 10.5) \times 9.81 + (18.25 - 16.5) \times 9.81 = 157.45kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (16.5 - 10.5) \times 9.7 + (18.25 - 16.5) \times 8.5 = 183.725kN/m^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 1 + 0.5 \times 183.72 = 92.86kN/m^2$$

Block perimeter $\xi = 105.7m$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 105.7 \times 3.5 = 369.94m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 92.86 \times 369.94 = 34353.38kN$$

• **Interacting Layer 5: [-20m] ↔ [-21.85m]**

Soil: Clay 2 (Sandy Clay – SaCl)

Effective column length in block/soil interaction zone $L_e = 1.85m$

$$\gamma_{sat} = 19.5kN/m^3 \quad \gamma_n = 18.7kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 9.7kN/m^3$$

$$c' = 18kPa \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (16.5 - 10.5) \times 19.5 + (20 - 16.5) \times 18.3 + (20.925 - 20) \times 19.5 = 391.078kN/m^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 + (16.5 - 10.5) \times 9.81 \\ + (20 - 16.5) \times 9.81 + (20.925 - 20) \times 9.81 = 183.692kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (16.5 - 10.5) \times 9.7 + (20 - 16.5) \times 8.5 + (20.925 - 20) \times 9.7 = 207.572kN/m^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 18 + 0.41 \times 207.57 = 104.1kN/m^2$$

Block perimeter $\xi = 105.7m$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 105.7 \times 1.85 = 195.54m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 104.1 \times 195.54 = 20355.81kN$$

• Total Shaft Resistance

Shaft resistances of all block/soil interaction layers are summed.

$$R_{s;k,gr} = \sum_{i=1}^5 Q_{si} = 18810.65 + 7151.32 + 44372.51 + 34353.38 + 20355.81 = \mathbf{125043.67kN}$$

Block Base Resistance

Effective shear strength angle at the block base: $\phi' = 20^\circ$

Elevation at the block base = -21.85m

Natural stresses at the block base have been calculated.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (16.5 - 10.5) \times 19.5 + (20 - 16.5) \times 18.3 + (21.85 - 20) \times 19.5 = 409.115kN/m^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 + (16.5 - 10.5) \times 9.81 \\ + (20 - 16.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (16.5 - 10.5) \times 9.7 + (20 - 16.5) \times 8.5 + (21.85 - 20) \times 9.7 = 216.545kN/m^2$$

Plastification angle $\psi_p = 0.4\pi$

Block base resistance was calculated for effective stresses using Equations (81), (82), and (83).

$$N_t = \left(\tan 20 + \sqrt{1 + \tan^2 20} \right)^2 e^{2 \times 0.4\pi \times \tan 20} = 5.091$$

$$f_b = 5.091 \times 216.54 = 1102.41kN/m^2$$

Block base area:

$$A_b = 648.7m^2$$

Base resistance:

$$R_{b;k,gr} = 1102.41 \times 648.7 = \mathbf{715171.91kN}$$

Block Bearing Capacity

Self-weight of the rigid columns within the block:

$$W_{p,b} = n_p \times W_p = 191 \times 105.75 = 20197.49kN$$

Area of the soil enclosed within the block:

$$A_s = Ab - n_p \times \left(\frac{\pi \times D^2}{4} \right) = 648.7 - 191 \times \left(\frac{\pi \times 0.6^2}{4} \right) = 594.69m^2$$

Self-weight of the soil enclosed within the block:

$$W_{s,b} = \sum_1^{10} \gamma_{n,i} L_{e,i} A_s = 17 \times 4.35 \times 594.69 + 17.5 \times 1.3 \times 594.69 + 18.7 \times 6 \times 594.69 + 17.2 \times 3.5 \times 594.69 + 18.7 \times 1.85 \times 594.69 + = 720560.6kN$$

Self-weight of the block:

$$W_b = W_{p,b} + W_{s,b} = 20197.49 + 720560.6 = 200802.81kN$$

Pore water pressure at the block base:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 + (16.5 - 10.5) \times 9.81 + (20 - 16.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766kN/m^2$$

The net self-weight of the block is determined by taking into account the pore water pressure at the base.

$$W_{b,net} = W_b - u_w \times A_b = 200802.81 - 192.77 \times 648.7 = 75755.74kN$$

Bearing capacity was obtained by applying Equation (62).

$$R_{c;k,gr} = R_{s;k,gr} + R_{b;k,gr} - W_b = 125043.67 + 715171.91 - 75755.74 = \mathbf{764459.84kN}$$

The group efficiency has been limited to 1 in order to remain on the safe side.

$$R_{c;k,gr} = n \times R_{c;k} = 191 \times 2486.91 = 474998.92kN$$

Design of Rigid Column Group

Axial design load on the rigid column group: $F_{c;d,gr} = 170000kN$

Partial factor $\gamma_R = 1.5$

Design group bearing capacity:

$$R_{c;d,gr} = \frac{R_{c;k,gr}}{\gamma_R} = \frac{474998.92}{1.5} = \mathbf{316665.95kN}$$

$$F_{c;d,gr} = 170000kN/m^2 \leq R_{c;d} = 316665.95kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{R_{c;k,gr}}{F_{c;d,gr}} = \frac{474998.92}{170000} = 2.79$$

15 “BLOCK A” Combined Bearing Capacity

The combined bearing capacity of the foundation system resting on rigid columns is being evaluated. The total capacity is obtained by combining the previously calculated shallow foundation bearing capacity with the bearing capacity of the rigid column group.

Combined bearing capacity:

$$q_{ult,comb} = q_{ult} + \frac{R_{c;k,gr}}{A} = 1757.88 + \frac{474998.92}{648.7} = \mathbf{2490.11kN/m^2}$$

Design combined bearing capacity:

$$q_{t,comb} = q_t + \frac{R_{c;d,gr}}{A} = 1255.63 + \frac{316665.95}{648.7} = \mathbf{1743.78kN/m^2}$$

16 “BLOCK B” Bearing Capacity of Shallow Foundation

The bearing capacity has been calculated using the Vesic method for effective stress analysis.

Foundation Geometry and Base Pressure

$B = 20m$ $L = 30m$ $D_f = 4.85m$ $q_0 = 300kN/m^2$ $P = 170000kN$ Foundation base elevation=-4.85m

Soil Profile

Fill: [-0m]-[-2.8m]

$$\gamma_n = 18.5kN/m^3$$

$$\gamma_{sat} = 19.4kN/m^3$$

Effective cohesion $c' = 0kN/m^2$

Internal friction angle for effective stress $\phi' = 26^\circ$

Silty Clay (Alluvium): [-2.8m]-[-9.2m]

$$\gamma_n = 17kN/m^3$$

$$\gamma_{sat} = 17.9kN/m^3$$

$$\text{Effective cohesion } c' = 4kN/m^2$$

Internal friction angle for effective stress $\phi' = 24^\circ$

Gravelly Clayey Sand: [-9.2m]-[-10.5m]

$$\gamma_n = 17.5kN/m^3$$

$$\gamma_{sat} = 19.3kN/m^3$$

$$\text{Effective cohesion } c' = 1kN/m^2$$

Internal friction angle for effective stress $\phi' = 28^\circ$

Clay (Sandy Clay with Silt – SaClSi): [-10.5m]-[-16.5m]

$$\gamma_n = 18.7kN/m^3$$

$$\gamma_{sat} = 19.5kN/m^3$$

$$\text{Effective cohesion } c' = 12kN/m^2$$

Internal friction angle for effective stress $\phi' = 20^\circ$

sand: [-16.5m]-[-20m]

$$\gamma_n = 17.2kN/m^3$$

$$\gamma_{sat} = 18.3kN/m^3$$

$$\text{Effective cohesion } c' = 1kN/m^2$$

Internal friction angle for effective stress $\phi' = 30^\circ$

Clay 2 (Sandy Clay – SaCl): [-20m]-[-40m]

$$\gamma_n = 18.7kN/m^3$$

$$\gamma_{sat} = 19.5kN/m^3$$

$$\text{Effective cohesion } c' = 18kN/m^2$$

Internal friction angle for effective stress $\phi' = 20^\circ$

Ground Water Table

$$GWT = -2.2m$$

Natural Stress Calculation at Foundation Base Level

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (4.85 - 2.8) \times 17.9 = 89.035kN/m^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (4.85 - 2.8) \times 9.81 = 25.996 kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (4.85 - 2.8) \times 8.1 = 63.065 kN/m^2$$

Eksantrisite

The effective foundation dimensions are determined using Equations (6) and (7):

$$B' = 20m$$

$$L' = 30m$$

Geotechnical Parameters and Groundwater Table (GWT) Effect

The unit weight of the soil above the foundation base is $\gamma = 13.003 kN/m^3$

The effective angle of internal friction of the soil above the foundation base is

$$\phi' = 25.15^\circ = 0.14\pi$$

The weighted average of the effective cohesion of the soil below the foundation base is

$$c' = 9.08 kPa$$

The weighted average of the effective angle of internal friction of the soil below the foundation base is $\phi' = 23.14^\circ = 0.129\pi$

Effect of Groundwater Table

The groundwater effect on γ in the third term has been considered.

For $0 < Y_{ASS} \leq D_f$, the submerged unit weight γ is used. The weighted average submerged unit weight of the soil below the foundation base is $\gamma = 9.129 kN/m^3$

Bearing Capacity Factors

The values of N_c , N_q , and N_γ were determined based on Equations (22), (23), and (40).

$$N_q^* = e^{\pi \tan 23.14} \tan^2 \left(45 + \frac{23.14}{2} \right) = 8.79$$

$$N_c = (8.79 - 1) \cot 23.14 = 18.22$$

$$N_q = e^{\pi \tan 25.15} \tan^2 \left(45 + \frac{25.15}{2} \right) = 10.84$$

$$N_\gamma = 2(8.79 + 1) \tan 23.14 = 8.36$$

Shape Factors

The shape factors were calculated using Equations (41), (42), and (43).

$$s_c = 1 + \frac{10.84}{18.22} \cdot \frac{20}{30} = 1.4$$

$$s_q = 1 + \frac{20}{30} \tan 25.15 = 1.31$$

$$s_\gamma = \max \left(1 - 0.4 \times \frac{20}{30} = 0.73; 0.6 \right) = 0.73$$

Depth Factors

Based on the calculations performed according to Equations (45), (46), (47) and (48):

$$\frac{4.85}{20} \leq 1 \rightarrow k = \frac{4.85}{20} = 0.2425$$

$$d_c = 1 + 0.4 \times 0.24 = 1.1$$

$$d_q = 1 + 2 \times \tan 25.15 \times (1 - \sin 25.15)^2 \times 0.24 = 1.08$$

$$d_\gamma = 1$$

Inclination Factors

Since there is no load inclination, the value of these factors is equal to 1.

$$i_q = 1$$

$$i_c = 1$$

$$i_\gamma = 1$$

Ground Factors (base on a slope)

Since there is no ground slope ($\beta = 0$), the value of these factors is equal to 1.

$$g_c = 1$$

$$g_q = 1$$

$$g_\gamma = 1$$

Base Factors (tilted base)

Taban eğimi olmadığı için ($\eta = 0$) bu faktörlerin değeri 1'e eşittir.

$$b_c = 1$$

$$b_q = 1$$

$$b_\gamma = 1$$

Bearing Capacity

$$c' = 9.08kPa$$

$$\phi' = 25.15^\circ (\text{for soil above the foundation base})$$

$$\phi' = 23.14^\circ (\text{for soil below the foundation base})$$

$$q = 63.06kN/m^2$$

$$N_c = 18.22 \quad N_q = 10.84 \quad N_\gamma = 8.36$$

$$s_c = 1.4 \quad s_q = 1.31 \quad s_\gamma = 0.73$$

$$d_c = 1.1 \quad d_q = 1.08 \quad d_\gamma = 1$$

$$i_c = 1 \quad i_q = 1 \quad i_\gamma = 1$$

$$g_c = 1 \quad g_q = 1 \quad g_\gamma = 1$$

$$b_c = 1 \quad b_q = 1 \quad b_\gamma = 1$$

$$B = 20m \quad B' = 20m \quad \gamma = 9.129kN/m^3$$

Based on effective stresses, the Vesic bearing capacity according to Equation (38):

$$q_{ult} = cN_c s_c d_c i_c g_c b_c + qN_q s_q d_q i_q g_q b_q + 0.5\gamma B N_\gamma s_\gamma d_\gamma i_\gamma g_\gamma b_\gamma$$

$$\begin{aligned} q_{ult} &= 9.08 \times 18.22 \times 1.4 \times 1.1 \times 1 \times 1 \times 1 \\ &\quad + 63.06 \times 10.84 \times 1.31 \times 1.08 \times 1 \times 1 \times 1 \\ &\quad + 0.5 \times 9.129 \times 20 \times 8.36 \times 0.73 \times 1 \times 1 \times 1 \times 1 \\ &= 1778.29kN/m^2 \end{aligned}$$

Design

$$\text{Contact Pressure } q_0 = 300kN/m^2$$

$$\text{Partial factor } \gamma_{R;v} = 1.4$$

Design bearing capacity (based on effective stresses):

$$q_t = \frac{q_{ult}}{\gamma_{R;v}} = \frac{1778.29}{1.4} = 1270.21kN$$

$$q_0 = 300kN/m^2 \leq q_t = 1270.21kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{q_{ult}}{q_0} = \frac{1778.29}{300} = 5.93$$

17 Bearing Capacity of “BLOCK B” Deep Foundation

Rigid column type: Jet grouting

Number of rigid columns= 170

Diameter of rigid column D= 60cm

Length of rigid column L= 17m

Rigid Column Cap

Geometry: Polygon

Coordinates of the rigid column cap: Polygon1: p1(X= 72.5676m Y= 22.6904m) ; p2(X= 72.5676m Y= 42.1904m) ; p3(X= 103.3176m Y= 42.1904m) ; p4(X= 103.3176m Y= 22.6904m) ;

Shaft Resistance of a Single Column

Shaft resistance is calculated individually for each soil layer interacting with the column, and their sum gives the total shaft resistance of the column.

- **Interacting Layer 1: [-4.85m] ↔ [-9.2m]**

Soil: Silty Clay (Alluvium))

Effective column length in rigid column/soil interaction zone $L_e = 4.35\text{m}$

$$\gamma_{sat} = 17.9\text{kN/m}^3 \quad \gamma_n = 17\text{kN/m}^3 \quad \gamma_w = 9.81\text{kN/m}^3 \quad \gamma' = 8.1\text{kN/m}^3$$

$$c' = 4\text{kPa} \quad \phi' = 24^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 24) \times 3^{0.5} \times \tan 24 = 0.46$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (7.025 - 2.8) \times 17.9 = 127.968\text{kN/m}^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (7.025 - 2.8) \times 9.81 = 47.333\text{kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (7.025 - 2.8) \times 8.1 = 80.682 \text{ kN/m}^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 4 + 0.46 \times 80.68 = 40.91 \text{ kN/m}^2$$

Lateral surface area of the rigid column:

$$A_s = \pi D L_e = \pi \times 0.6 \times 4.35 = 8.2 \text{ m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 40.91 \times 8.2 = 335.46 \text{ kN}$$

- **Interacting Layer 2: [-9.2m] ↔ [-10.5m]**

Soil: Gravelly Clayey Sand

Effective column length in rigid column/soil interaction zone $L_e = 1.3 \text{ m}$

$$\gamma_{sat} = 19.3 \text{ kN/m}^3 \quad \gamma_n = 17.5 \text{ kN/m}^3 \quad \gamma_w = 9.81 \text{ kN/m}^3 \quad \gamma' = 9.5 \text{ kN/m}^3$$

$$c' = 1 \text{ kPa} \quad \phi' = 28^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 28) \times 3^{0.5} \times \tan 28 = 0.49$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 \\ &+ (9.2 - 2.8) \times 17.9 + (9.85 - 9.2) \times 19.3 = 179.445 \text{ kN/m}^2 \end{aligned}$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (9.85 - 9.2) \times 9.81 = 75.047 \text{ kN/m}^2$$

Effective stress:

$$\begin{aligned} \sigma' &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 \\ &+ (9.2 - 2.8) \times 8.1 + (9.85 - 9.2) \times 9.5 = 104.475 \text{ kN/m}^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 1 + 0.49 \times 104.47 = 52.05kN/m^2$$

Lateral surface area of the rigid column:

$$A_s = \pi DL_e = \pi \times 0.6 \times 1.3 = 2.45m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 52.05 \times 2.45 = 127.53kN$$

• **Interacting Layer 3: [-10.5m] ↔ [-16.5m]**

Soil: Clay (Sandy Clay with Silt – SaClSi)

Effective column length in rigid column/soil interaction zone $L_e = 6m$

$$\gamma_{sat} = 19.5kN/m^3 \quad \gamma_n = 18.7kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 9.7kN/m^3$$

$$c' = 12kPa \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma = & +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 \\ & + (10.5 - 9.2) \times 19.3 + (13.5 - 10.5) \times 19.5 = 250.49kN/m^2 \end{aligned}$$

Pore water pressure:

$$\begin{aligned} u_w = & +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 \\ & + (10.5 - 9.2) \times 9.81 + (13.5 - 10.5) \times 9.81 = 110.853kN/m^2 \end{aligned}$$

Effective stress:

$$\begin{aligned} \sigma' = & +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 \\ & + (10.5 - 9.2) \times 9.5 + (13.5 - 10.5) \times 9.7 = 139.75kN/m^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 12 + 0.41 \times 139.75 = 69.97kN/m^2$$

Lateral surface area of the rigid column:

$$A_s = \pi DL_e = \pi \times 0.6 \times 6 = 11.31m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 69.97 \times 11.31 = 791.32kN$$

• **Interacting Layer 4: [-16.5m] ↔ [-20m]**

Soil: sand

Effective column length in rigid column/soil interaction zone $L_e = 3.5m$

$$\gamma_{sat} = 18.3kN/m^3 \quad \gamma_n = 17.2kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 8.5kN/m^3$$

$$c' = 1kPa \quad \phi' = 30^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 30) \times 3^{0.5} \times \tan 30 = 0.5$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (16.5 - 10.5) \times 19.5 + (18.25 - 16.5) \times 18.3 = 341.015kN/m^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ + (16.5 - 10.5) \times 9.81 + (18.25 - 16.5) \times 9.81 = 157.45kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (16.5 - 10.5) \times 9.7 + (18.25 - 16.5) \times 8.5 = 183.725kN/m^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 1 + 0.5 \times 183.72 = 92.86 \text{ kN/m}^2$$

Lateral surface area of the rigid column:

$$A_s = \pi D L_e = \pi \times 0.6 \times 3.5 = 6.6 \text{ m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 92.86 \times 6.6 = 612.65 \text{ kN}$$

• **Interacting Layer 5: [-20m] ↔ [-21.85m]**

Soil: Clay 2 (Sandy Clay – SaCl)

Effective column length in rigid column/soil interaction zone $L_e = 1.85 \text{ m}$

$$\gamma_{sat} = 19.5 \text{ kN/m}^3 \quad \gamma_n = 18.7 \text{ kN/m}^3 \quad \gamma_w = 9.81 \text{ kN/m}^3 \quad \gamma' = 9.7 \text{ kN/m}^3$$

$$c' = 18 \text{ kPa} \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (16.5 - 10.5) \times 19.5 + (20 - 16.5) \times 18.3 + (20.925 - 20) \times 19.5 = 391.078 \text{ kN/m}^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 + (16.5 - 10.5) \times 9.81 \\ + (20 - 16.5) \times 9.81 + (20.925 - 20) \times 9.81 = 183.692 \text{ kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (16.5 - 10.5) \times 9.7 + (20 - 16.5) \times 8.5 + (20.925 - 20) \times 9.7 = 207.572 \text{ kN/m}^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 18 + 0.41 \times 207.57 = 104.1kN/m^2$$

Lateral surface area of the rigid column:

$$A_s = \pi DL_e = \pi \times 0.6 \times 1.85 = 3.49m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 104.1 \times 3.49 = 363.02kN$$

• Total Shaft Resistance

Shaft resistances of all rigid column/soil interaction layers are summed.

$$R_{s;k} = \sum_{i=1}^5 Q_{si} = 335.46 + 127.53 + 791.32 + 612.65 + 363.02 = \mathbf{2229.98kN}$$

Tip Resistance of a Single Column

Effective shear strength angle at the column tip: $\phi' = 20^\circ$

Tip elevation of the rigid column = -21.85m

Natural stresses at the tip of the rigid column have been calculated.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (16.5 - 10.5) \times 19.5 + (20 - 16.5) \times 18.3 + (21.85 - 20) \times 19.5 = 409.115kN/m^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 + (16.5 - 10.5) \times 9.81 \\ + (20 - 16.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (16.5 - 10.5) \times 9.7 + (20 - 16.5) \times 8.5 + (21.85 - 20) \times 9.7 = 216.545kN/m^2$$

Plastification angle $\psi_p = 0.4\pi$

Tip resistance was calculated for effective stresses using Equations (81), (82), and (83).

$$N_t = \left(\tan 20 + \sqrt{1 + \tan^2 20} \right)^2 e^{2 \times 0.4\pi \times \tan 20} = 5.091$$

$$f_b = 5.091 \times 216.54 = 1102.41kN/m^2$$

Cross-sectional area of the rigid column:

$$A_b = \frac{\pi D^2}{4} = \frac{\pi \times 0.6^2}{4} = 0.28m^2$$

Tip resistance:

$$R_{b;k} = 1102.41 \times 0.28 = \mathbf{308.69kN}$$

Bearing Capacity of a Single Column

The unit weight of a jet grouting column is calculated as the weighted average of the unit weights of the mixtures in the interacting soil layers.

$$\gamma_{c,av} = \frac{\sum_{i=1}^8 \gamma_{mix,i} \times L_{e,i}}{L_p} = \frac{22 \times 4.35 + 22 \times 1.3 + 22 \times 6 + 22 \times 3.5 + 22 \times 1.85}{17} = 22kN/m^3$$

$$W_p = \gamma_{c,av} L_p A_b = 22 \times 17 \times 0.28 = 105.75kN$$

Pore water pressure at the tip of the rigid column:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 + (16.5 - 10.5) \times 9.81 + (20 - 16.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766kN/m^2$$

The net self-weight of the column is determined by taking into account the pore water pressure at the column tip.

$$W_{p,net} = W_p - u_w \times A_b = 105.75 - 192.77 \times 0.28 = 51.77kN$$

Bearing capacity was obtained by applying Equation (62).

$$R_{c;k} = R_{s;k} + R_{b;k} - W_p = 2229.98 + 308.69 - 51.77 = \mathbf{2486.91kN}$$

Design of a Single Column

Design axial load on the rigid column:: $F_{c;d} = 1115.36kN$

Partial factors: $\gamma_s = 1.5$ $\gamma_b = 2$

Design bearing capacity:

$$R_{c;d} = \frac{R_{s;k}}{\gamma_{Rs}} + \frac{R_{b;k}}{\gamma_{Ru}} = \frac{2229.98}{1.5} + \frac{308.69}{2} = \mathbf{1641kN}$$

$$F_{c;d} = 1115.36kN/m^2 \leq R_{c;d} = 1641kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{R_{c;k}}{F_{c;d}} = \frac{2486.91}{1115.36} = 2.23$$

Bearing Capacity of Rigid Column Group

The bearing capacity of the rigid column group was calculated using the Terzaghi block method.

Block Shaft Resistance

Shaft resistance is calculated individually for each soil layer interacting with the column, and their sum gives the total shaft resistance of the block.

- **Interacting Layer 1: [-4.85m] ↔ [-9.2m]**

Soil: Silty Clay (Alluvium))

Effective column length in block/soil interaction zone $L_e = 4.35m$

$$\gamma_{sat} = 17.9kN/m^3 \quad \gamma_n = 17kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 8.1kN/m^3$$

$$c' = 4kPa \quad \phi' = 24^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 24) \times 3^{0.5} \times \tan 24 = 0.46$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (7.025 - 2.8) \times 17.9 = 127.968kN/m^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (7.025 - 2.8) \times 9.81 = 47.333kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (7.025 - 2.8) \times 8.1 = 80.682kN/m^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 4 + 0.46 \times 80.68 = 40.91kN/m^2$$

Block perimeter $\xi = 100.5m$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 100.5 \times 4.35 = 437.17m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 40.91 \times 437.17 = 17885.82kN$$

• **Interacting Layer 2: [-9.2m] ↔ [-10.5m]**

Soil: Gravelly Clayey Sand

Effective column length in block/soil interaction zone $L_e = 1.3m$

$$\gamma_{sat} = 19.3kN/m^3 \quad \gamma_n = 17.5kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 9.5kN/m^3$$

$$c' = 1kPa \quad \phi' = 28^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 28) \times 3^{0.5} \times \tan 28 = 0.49$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 \\ &+ (9.2 - 2.8) \times 17.9 + (9.85 - 9.2) \times 19.3 = 179.445kN/m^2 \end{aligned}$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (9.85 - 9.2) \times 9.81 = 75.047kN/m^2$$

Effective stress:

$$\begin{aligned} \sigma' &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 \\ &+ (9.2 - 2.8) \times 8.1 + (9.85 - 9.2) \times 9.5 = 104.475kN/m^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 1 + 0.49 \times 104.47 = 52.05kN/m^2$$

Block perimeter $\xi = 100.5m$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 100.5 \times 1.3 = 130.65m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 52.05 \times 130.65 = 6799.72kN$$

• **Interacting Layer 3: [-10.5m] ↔ [-16.5m]**

Soil: Clay (Sandy Clay with Silt – SaClSi)

Effective column length in block/soil interaction zone $L_e = 6m$

$$\gamma_{sat} = 19.5kN/m^3 \quad \gamma_n = 18.7kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 9.7kN/m^3$$

$$c' = 12kPa \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma = & +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 \\ & + (10.5 - 9.2) \times 19.3 + (13.5 - 10.5) \times 19.5 = 250.49kN/m^2 \end{aligned}$$

Pore water pressure:

$$\begin{aligned} u_w = & +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 \\ & + (10.5 - 9.2) \times 9.81 + (13.5 - 10.5) \times 9.81 = 110.853kN/m^2 \end{aligned}$$

Effective stress:

$$\begin{aligned} \sigma' = & +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 \\ & + (10.5 - 9.2) \times 9.5 + (13.5 - 10.5) \times 9.7 = 139.75kN/m^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 12 + 0.41 \times 139.75 = 69.97kN/m^2$$

Block perimeter $\xi = 100.5m$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 100.5 \times 6 = 603m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 69.97 \times 603 = 42190.91kN$$

• **Interacting Layer 4: [-16.5m] ↔ [-20m]**

Soil: sand

Effective column length in block/soil interaction zone $L_e = 3.5\text{m}$

$$\gamma_{sat} = 18.3\text{kN/m}^3 \quad \gamma_n = 17.2\text{kN/m}^3 \quad \gamma_w = 9.81\text{kN/m}^3 \quad \gamma' = 8.5\text{kN/m}^3$$

$$c' = 1\text{kPa} \quad \phi' = 30^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 30) \times 3^{0.5} \times \tan 30 = 0.5$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma = & +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ & + (16.5 - 10.5) \times 19.5 + (18.25 - 16.5) \times 18.3 = 341.015\text{kN/m}^2 \end{aligned}$$

Pore water pressure:

$$\begin{aligned} u_w = & +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 \\ & + (16.5 - 10.5) \times 9.81 + (18.25 - 16.5) \times 9.81 = 157.45\text{kN/m}^2 \end{aligned}$$

Effective stress:

$$\begin{aligned} \sigma' = & +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ & + (16.5 - 10.5) \times 9.7 + (18.25 - 16.5) \times 8.5 = 183.725\text{kN/m}^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 1 + 0.5 \times 183.72 = 92.86\text{kN/m}^2$$

Block perimeter $\xi = 100.5\text{m}$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 100.5 \times 3.5 = 351.75\text{m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 92.86 \times 351.75 = 32664.38\text{kN}$$

• **Interacting Layer 5: [-20m] ↔ [-21.85m]**

Soil: Clay 2 (Sandy Clay – SaCl)

Effective column length in block/soil interaction zone $L_e = 1.85\text{m}$

$$\gamma_{sat} = 19.5\text{kN/m}^3 \quad \gamma_n = 18.7\text{kN/m}^3 \quad \gamma_w = 9.81\text{kN/m}^3 \quad \gamma' = 9.7\text{kN/m}^3$$

$$c' = 18\text{kPa} \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (16.5 - 10.5) \times 19.5 + (20 - 16.5) \times 18.3 + (20.925 - 20) \times 19.5 = 391.078\text{kN/m}^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 + (16.5 - 10.5) \times 9.81 \\ + (20 - 16.5) \times 9.81 + (20.925 - 20) \times 9.81 = 183.692\text{kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (16.5 - 10.5) \times 9.7 + (20 - 16.5) \times 8.5 + (20.925 - 20) \times 9.7 = 207.572\text{kN/m}^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 18 + 0.41 \times 207.57 = 104.1\text{kN/m}^2$$

Block perimeter $\xi = 100.5\text{m}$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 100.5 \times 1.85 = 185.93\text{m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 104.1 \times 185.93 = 19355\text{kN}$$

• Total Shaft Resistance

Shaft resistances of all block/soil interaction layers are summed.

$$R_{s;k,gr} = \sum_{i=1}^5 Q_{si} = 17885.82 + 6799.72 + 42190.91 + 32664.38 + 19355 = \mathbf{118895.84kN}$$

Block Base Resistance

Effective shear strength angle at the block base: $\phi' = 20^\circ$

Elevation at the block base = -21.85m

Natural stresses at the block base have been calculated.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 + (10.5 - 9.2) \times 19.3 \\ + (16.5 - 10.5) \times 19.5 + (20 - 16.5) \times 18.3 + (21.85 - 20) \times 19.5 = 409.115kN/m^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 + (16.5 - 10.5) \times 9.81 \\ + (20 - 16.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 + (10.5 - 9.2) \times 9.5 \\ + (16.5 - 10.5) \times 9.7 + (20 - 16.5) \times 8.5 + (21.85 - 20) \times 9.7 = 216.545kN/m^2$$

Plastification angle $\psi_p = 0.4\pi$

Block base resistance was calculated for effective stresses using Equations (81), (82), and (83).

$$N_t = \left(\tan 20 + \sqrt{1 + \tan^2 20} \right)^2 e^{2 \times 0.4\pi \times \tan 20} = 5.091$$

$$f_b = 5.091 \times 216.54 = 1102.41kN/m^2$$

Block base area:

$$A_b = 599.63m^2$$

Base resistance:

$$R_{b;k,gr} = 1102.41 \times 599.63 = \mathbf{661071.19kN}$$

Block Bearing Capacity

Self-weight of the rigid columns within the block:

$$W_{p,b} = n_p \times W_p = 170 \times 105.75 = 17976.82kN$$

Area of the soil enclosed within the block:

$$A_s = Ab - n_p \times \left(\frac{\pi \times D^2}{4} \right) = 599.63 - 170 \times \left(\frac{\pi \times 0.6^2}{4} \right) = 551.56m^2$$

Self-weight of the soil enclosed within the block:

$$W_{s,b} = \sum_1^{10} \gamma_{n,i} L_{e,i} A_s = 17 \times 4.35 \times 551.56 + 17.5 \times 1.3 \times 551.56 + 18.7 \times 6 \times 551.56 + 17.2 \times 3.5 \times 551.56 + 18.7 \times 1.85 \times 551.56 + = 888066.2kN$$

Self-weight of the block:

$$W_b = W_{p,b} + W_{s,b} = 17976.82 + 888066.2 = 185482.42kN$$

Pore water pressure at the block base:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 + (16.5 - 10.5) \times 9.81 + (20 - 16.5) \times 9.81 + (21.85 - 20) \times 9.81 = 192.766kN/m^2$$

The net self-weight of the block is determined by taking into account the pore water pressure at the base.

$$W_{b,net} = W_b - u_w \times A_b = 185482.42 - 192.77 \times 599.63 = 69894.81kN$$

Bearing capacity was obtained by applying Equation (62).

$$R_{c;k,gr} = R_{s;k,gr} + R_{b;k,gr} - W_b = 118895.84 + 661071.19 - 69894.81 = \mathbf{710072.23kN}$$

The group efficiency has been limited to 1 in order to remain on the safe side.

$$R_{c;k,gr} = n \times R_{c;k} = 170 \times 2486.91 = 422773.91kN$$

Design of Rigid Column Group

Axial design load on the rigid column group: $F_{c;d,gr} = 170000kN$

Partial factor $\gamma_R = 1.5$

Design group bearing capacity:

$$R_{c;d,gr} = \frac{R_{c;k,gr}}{\gamma_R} = \frac{422773.91}{1.5} = \mathbf{281849.27kN}$$

$$F_{c;d,gr} = 170000kN/m^2 \leq R_{c;d} = 281849.27kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{R_{c;k,gr}}{F_{c;d,gr}} = \frac{422773.91}{170000} = 2.49$$

18 “BLOCK B” Combined Bearing Capacity

The combined bearing capacity of the foundation system resting on rigid columns is being evaluated. The total capacity is obtained by combining the previously calculated shallow foundation bearing capacity with the bearing capacity of the rigid column group.

Combined bearing capacity:

$$q_{ult,comb} = q_{ult} + \frac{R_{c;k,gr}}{A} = 1778.29 + \frac{422773.91}{599.63} = \mathbf{2483.36kN/m^2}$$

Design combined bearing capacity:

$$q_{t,comb} = q_t + \frac{R_{c;d,gr}}{A} = 1270.21 + \frac{281849.27}{599.63} = \mathbf{1740.25kN/m^2}$$

19 “BLOCK F” Bearing Capacity of Shallow Foundation

The bearing capacity has been calculated using the Vesic method for effective stress analysis.

Foundation Geometry and Base Pressure

$B = 16.5m$ $L = 19.5m$ $D_f = 3.95m$ $q_0 = 140kN/m^2$ $P = 35000kN$ Foundation base elevation=-3.95m

Soil Profile

Fill: [-0m]-[-2.8m]

$$\gamma_n = 18.5kN/m^3$$

$$\gamma_{sat} = 19.4kN/m^3$$

Effective cohesion $c' = 0kN/m^2$

Internal friction angle for effective stress $\phi' = 26^\circ$

Silty Clay (Alluvium): [-2.8m]-[-9.2m]

$$\gamma_n = 17kN/m^3$$

$$\gamma_{sat} = 17.9kN/m^3$$

Effective cohesion $c' = 4kN/m^2$

Internal friction angle for effective stress $\phi' = 24^\circ$

Gravelly Clayey Sand: [-9.2m]-[-10.5m]

$$\gamma_n = 17.5kN/m^3$$

$$\gamma_{sat} = 19.3kN/m^3$$

Effective cohesion $c' = 1kN/m^2$

Internal friction angle for effective stress $\phi' = 28^\circ$

Clay (Sandy Clay with Silt – SaClSi): [-10.5m]-[-16.5m]

$$\gamma_n = 18.7kN/m^3$$

$$\gamma_{sat} = 19.5kN/m^3$$

Effective cohesion $c' = 12kN/m^2$

Internal friction angle for effective stress $\phi' = 20^\circ$

sand: [-16.5m]-[-20m]

$$\gamma_n = 17.2kN/m^3$$

$$\gamma_{sat} = 18.3kN/m^3$$

Effective cohesion $c' = 1kN/m^2$

Internal friction angle for effective stress $\phi' = 30^\circ$

Clay 2 (Sandy Clay – SaCl): [-20m]-[-40m]

$$\gamma_n = 18.7kN/m^3$$

$$\gamma_{sat} = 19.5kN/m^3$$

Effective cohesion $c' = 18kN/m^2$

Internal friction angle for effective stress $\phi' = 20^\circ$

Ground Water Table

$$GWT = -2.2m$$

Natural Stress Calculation at Foundation Base Level

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (3.95 - 2.8) \times 17.9 = 72.925kN/m^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (3.95 - 2.8) \times 9.81 = 17.168kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (3.95 - 2.8) \times 8.1 = 55.775kN/m^2$$

Eksantrisite

The effective foundation dimensions are determined using Equations (6) and (7):

$$B' = 16.5m$$

$$L' = 19.5m$$

Geotechnical Parameters and Groundwater Table (GWT) Effect

The unit weight of the soil above the foundation base is $\gamma = 14.12kN/m^3$

The effective angle of internal friction of the soil above the foundation base is

$$\phi' = 25.42^\circ = 0.141\pi$$

The weighted average of the effective cohesion of the soil below the foundation base is

$$c' = 6.42kPa$$

The weighted average of the effective angle of internal friction of the soil below the foundation base is $\phi' = 24.02^\circ = 0.133\pi$

Effect of Groundwater Table

The groundwater effect on γ in the third term has been considered.

For $0 < Y_{ASS} \leq D_f$, the submerged unit weight γ is used. The weighted average submerged unit weight of the soil below the foundation base is $\gamma = 8.921kN/m^3$

Bearing Capacity Factors

The values of N_c , N_q , and N_γ were determined based on Equations (22), (23), and (40).

$$N_q^* = e^{\pi \tan 24.02} \tan^2 \left(45 + \frac{24.02}{2} \right) = 9.63$$

$$N_c = (9.63 - 1) \cot 24.02 = 19.36$$

$$N_q = e^{\pi \tan 25.42} \tan^2 \left(45 + \frac{25.42}{2} \right) = 11.14$$

$$N_\gamma = 2(9.63 + 1) \tan 24.02 = 9.47$$

Shape Factors

The shape factors were calculated using Equations (41), (42), and (43).

$$s_c = 1 + \frac{11.14}{19.36} \cdot \frac{16.5}{19.5} = 1.49$$

$$s_q = 1 + \frac{16.5}{19.5} \tan 25.42 = 1.4$$

$$s_\gamma = \max \left(1 - 0.4 \times \frac{16.5}{19.5} = 0.66; 0.6 \right) = 0.66$$

Depth Factors

Based on the calculations performed according to Equations (45), (46), (47) and (48):

$$\frac{3.95}{16.5} \leq 1 \rightarrow k = \frac{3.95}{16.5} = 0.2393939393939394$$

$$d_c = 1 + 0.4 \times 0.24 = 1.1$$

$$d_q = 1 + 2 \times \tan 25.42 \times (1 - \sin 25.42)^2 \times 0.24 = 1.07$$

$$d_\gamma = 1$$

Inclination Factors

Since there is no load inclination, the value of these factors is equal to 1.

$$i_q = 1$$

$$i_c = 1$$

$$i_\gamma = 1$$

Ground Factors (base on a slope)

Since there is no ground slope ($\beta = 0$), the value of these factors is equal to 1.

$$g_c = 1$$

$$g_q = 1$$

$$g_\gamma = 1$$

Base Factors (tilted base)

Taban eğimi olmadığı için ($\eta = 0$) bu faktörlerin değeri 1'e eşittir.

$$b_c = 1$$

$$b_q = 1$$

$$b_\gamma = 1$$

Bearing Capacity

$$c' = 6.42kPa$$

$$\phi' = 25.42^\circ (\text{for soil above the foundation base})$$

$$\phi' = 24.02^\circ (\text{for soil below the foundation base})$$

$$q = 55.78kN/m^2$$

$$N_c = 19.36 \quad N_q = 11.14 \quad N_\gamma = 9.47$$

$$s_c = 1.49 \quad s_q = 1.4 \quad s_\gamma = 0.66$$

$$d_c = 1.1 \quad d_q = 1.07 \quad d_\gamma = 1$$

$$i_c = 1 \quad i_q = 1 \quad i_\gamma = 1$$

$$g_c = 1 \quad g_q = 1 \quad g_\gamma = 1$$

$$b_c = 1 \quad b_q = 1 \quad b_\gamma = 1$$

$$B = 16.5m \quad B' = 16.5m \quad \gamma = 8.921kN/m^3$$

Based on effective stresses, the Vesic bearing capacity according to Equation (38):

$$q_{ult} = cN_c s_c d_c i_c g_c b_c + qN_q s_q d_q i_q g_q b_q + 0.5\gamma B N_\gamma s_\gamma d_\gamma i_\gamma g_\gamma b_\gamma$$

$$\begin{aligned} q_{ult} &= 6.42 \times 19.36 \times 1.49 \times 1.1 \times 1 \times 1 \times 1 \\ &\quad + 55.78 \times 11.14 \times 1.4 \times 1.07 \times 1 \times 1 \times 1 \\ &\quad + 0.5 \times 8.921 \times 16.5 \times 9.47 \times 0.66 \times 1 \times 1 \times 1 \times 1 \\ &= 1599.68kN/m^2 \end{aligned}$$

Design

$$\text{Contact Pressure } q_0 = 140kN/m^2$$

$$\text{Partial factor } \gamma_{R;v} = 1.4$$

Design bearing capacity (based on effective stresses):

$$q_t = \frac{q_{ult}}{\gamma_{R;v}} = \frac{1599.68}{1.4} = 1142.63kN$$

$$q_0 = 140kN/m^2 \leq q_t = 1142.63kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{q_{ult}}{q_0} = \frac{1599.68}{140} = 11.43$$

20 Bearing Capacity of “BLOCK F” Deep Foundation

Rigid column type: Jet grouting

Number of rigid columns= 99

Diameter of rigid column D= 60cm

Length of rigid column L= 8m

Rigid Column Cap

Geometry: Polygon

Coordinates of the rigid column cap: Polygon1: p1(X= 44.3676m Y= 23.6404m) ; p2(X= 44.3676m Y= 40.5404m) ; p3(X= 64.2676m Y= 40.5404m) ; p4(X= 64.2676m Y= 23.5404m) ;

Shaft Resistance of a Single Column

Shaft resistance is calculated individually for each soil layer interacting with the column, and their sum gives the total shaft resistance of the column.

- **Interacting Layer 1: [-3.95m] ↔ [-9.2m]**

Soil: Silty Clay (Alluvium))

Effective column length in rigid column/soil interaction zone $L_e = 5.25\text{m}$

$$\gamma_{sat} = 17.9\text{kN/m}^3 \quad \gamma_n = 17\text{kN/m}^3 \quad \gamma_w = 9.81\text{kN/m}^3 \quad \gamma' = 8.1\text{kN/m}^3$$

$$c' = 4\text{kPa} \quad \phi' = 24^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 24) \times 3^{0.5} \times \tan 24 = 0.46$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (6.575 - 2.8) \times 17.9 = 119.913\text{kN/m}^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (6.575 - 2.8) \times 9.81 = 42.919\text{kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (6.575 - 2.8) \times 8.1 = 77.038\text{kN/m}^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 4 + 0.46 \times 77.04 = 39.24\text{kN/m}^2$$

Lateral surface area of the rigid column:

$$A_s = \pi D L_e = \pi \times 0.6 \times 5.25 = 9.9\text{m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 39.24 \times 9.9 = 388.37kN$$

• **Interacting Layer 2: [-9.2m] ↔ [-10.5m]**

Soil: Gravelly Clayey Sand

Effective column length in rigid column/soil interaction zone $L_e = 1.3m$

$$\gamma_{sat} = 19.3kN/m^3 \quad \gamma_n = 17.5kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 9.5kN/m^3$$

$$c' = 1kPa \quad \phi' = 28^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 28) \times 3^{0.5} \times \tan 28 = 0.49$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 \\ &+ (9.2 - 2.8) \times 17.9 + (9.85 - 9.2) \times 19.3 = 179.445kN/m^2 \end{aligned}$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (9.85 - 9.2) \times 9.81 = 75.047kN/m^2$$

Effective stress:

$$\begin{aligned} \sigma' &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 \\ &+ (9.2 - 2.8) \times 8.1 + (9.85 - 9.2) \times 9.5 = 104.475kN/m^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 1 + 0.49 \times 104.47 = 52.05kN/m^2$$

Lateral surface area of the rigid column:

$$A_s = \pi DL_e = \pi \times 0.6 \times 1.3 = 2.45m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 52.05 \times 2.45 = 127.53kN$$

• **Interacting Layer 3: [-10.5m] ↔ [-11.95m]**

Soil: Clay (Sandy Clay with Silt – SaClSi)

Effective column length in rigid column/soil interaction zone $L_e = 1.45\text{m}$

$$\gamma_{sat} = 19.5\text{kN/m}^3 \quad \gamma_n = 18.7\text{kN/m}^3 \quad \gamma_w = 9.81\text{kN/m}^3 \quad \gamma' = 9.7\text{kN/m}^3$$

$$c' = 12\text{kPa} \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma = & +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 \\ & + (10.5 - 9.2) \times 19.3 + (11.225 - 10.5) \times 19.5 = 206.128\text{kN/m}^2 \end{aligned}$$

Pore water pressure:

$$\begin{aligned} u_w = & +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 \\ & + (10.5 - 9.2) \times 9.81 + (11.225 - 10.5) \times 9.81 = 88.535\text{kN/m}^2 \end{aligned}$$

Effective stress:

$$\begin{aligned} \sigma' = & +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 \\ & + (10.5 - 9.2) \times 9.5 + (11.225 - 10.5) \times 9.7 = 117.682\text{kN/m}^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 12 + 0.41 \times 117.68 = 60.81\text{kN/m}^2$$

Lateral surface area of the rigid column:

$$A_s = \pi DL_e = \pi \times 0.6 \times 1.45 = 2.73\text{m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 60.81 \times 2.73 = 166.22\text{kN}$$

• Total Shaft Resistance

Shaft resistances of all rigid column/soil interaction layers are summed.

$$R_{s;k} = \sum_{i=1}^3 Q_{si} = 388.37 + 127.53 + 166.22 = \mathbf{682.12kN}$$

Tip Resistance of a Single Column

Effective shear strength angle at the column tip: $\phi' = 20^\circ$

Tip elevation of the rigid column = -11.95m

Natural stresses at the tip of the rigid column have been calculated.

Total stress:

$$\begin{aligned} \sigma &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 \\ &+ (10.5 - 9.2) \times 19.3 + (11.95 - 10.5) \times 19.5 = 220.265kN/m^2 \end{aligned}$$

Pore water pressure:

$$\begin{aligned} u_w &= +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 \\ &+ (10.5 - 9.2) \times 9.81 + (11.95 - 10.5) \times 9.81 = 95.647kN/m^2 \end{aligned}$$

Effective stress:

$$\begin{aligned} \sigma' &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 \\ &+ (10.5 - 9.2) \times 9.5 + (11.95 - 10.5) \times 9.7 = 124.715kN/m^2 \end{aligned}$$

Plastification angle $\psi_p = 0.4\pi$

Tip resistance was calculated for effective stresses using Equations (81), (82), and (83).

$$N_t = \left(\tan 20 + \sqrt{1 + \tan^2 20} \right)^2 e^{2 \times 0.4\pi \times \tan 20} = 5.091$$

$$f_b = 5.091 \times 124.71 = 634.9kN/m^2$$

Cross-sectional area of the rigid column:

$$A_b = \frac{\pi D^2}{4} = \frac{\pi \times 0.6^2}{4} = 0.28m^2$$

Tip resistance:

$$R_{b;k} = 634.9 \times 0.28 = \mathbf{177.79kN}$$

Bearing Capacity of a Single Column

The unit weight of a jet grouting column is calculated as the weighted average of the unit weights of the mixtures in the interacting soil layers.

$$\gamma_{c,av} = \frac{\sum_{i=1}^8 \gamma_{mix,i} \times L_{e,i}}{L_p} = \frac{22 \times 5.25 + 22 \times 1.3 + 22 \times 1.45}{8} = 22kN/m^3$$

$$W_p = \gamma_{c,av} L_p A_b = 22 \times 8 \times 0.28 = 49.76 kN$$

Pore water pressure at the tip of the rigid column:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 \\ + (10.5 - 9.2) \times 9.81 + (11.95 - 10.5) \times 9.81 = 95.647 kN/m^2$$

The net self-weight of the column is determined by taking into account the pore water pressure at the column tip.

$$W_{p,net} = W_p - u_w \times A_b = 49.76 - 95.65 \times 0.28 = 22.98 kN$$

Bearing capacity was obtained by applying Equation (62).

$$R_{c;k} = R_{s;k} + R_{b;k} - W_p = 682.12 + 177.79 - 22.98 = \mathbf{836.92 kN}$$

Design of a Single Column

Design axial load on the rigid column:: $F_{c;d} = 407.82 kN$

Partial factors: $\gamma_s = 1.5$ $\gamma_b = 2$

Design bearing capacity:

$$R_{c;d} = \frac{R_{s;k}}{\gamma_{Rs}} + \frac{R_{b;k}}{\gamma_{Ru}} = \frac{682.12}{1.5} + \frac{177.79}{2} = \mathbf{543.64 kN}$$

$$F_{c;d} = 407.82 kN/m^2 \leq R_{c;d} = 543.64 kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{R_{c;k}}{F_{c;d}} = \frac{836.92}{407.82} = 2.05$$

Bearing Capacity of Rigid Column Group

The bearing capacity of the rigid column group was calculated using the Terzaghi block method.

Block Shaft Resistance

Shaft resistance is calculated individually for each soil layer interacting with the column, and their sum gives the total shaft resistance of the block.

- **Interacting Layer 1: [-3.95m] ↔ [-9.2m]**

Soil: Silty Clay (Alluvium))

Effective column length in block/soil interaction zone $L_e = 5.25m$

$$\gamma_{sat} = 17.9kN/m^3 \quad \gamma_n = 17kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 8.1kN/m^3$$

$$c' = 4kPa \quad \phi' = 24^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 24) \times 3^{0.5} \times \tan 24 = 0.46$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (6.575 - 2.8) \times 17.9 = 119.913kN/m^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (6.575 - 2.8) \times 9.81 = 42.919kN/m^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (6.575 - 2.8) \times 8.1 = 77.038kN/m^2$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 4 + 0.46 \times 77.04 = 39.24kN/m^2$$

Block perimeter $\xi = 73.7m$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 73.7 \times 5.25 = 386.93m^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 39.24 \times 386.93 = 15184.8kN$$

- **Interacting Layer 2: [-9.2m] ↔ [-10.5m]**

Soil: Gravelly Clayey Sand

Effective column length in block/soil interaction zone $L_e = 1.3m$

$$\gamma_{sat} = 19.3kN/m^3 \quad \gamma_n = 17.5kN/m^3 \quad \gamma_w = 9.81kN/m^3 \quad \gamma' = 9.5kN/m^3$$

$$c' = 1kPa \quad \phi' = 28^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 28) \times 3^{0.5} \times \tan 28 = 0.49$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 \\ &+ (9.2 - 2.8) \times 17.9 + (9.85 - 9.2) \times 19.3 = 179.445 \text{ kN/m}^2 \end{aligned}$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (9.85 - 9.2) \times 9.81 = 75.047 \text{ kN/m}^2$$

Effective stress:

$$\begin{aligned} \sigma' &= +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 \\ &+ (9.2 - 2.8) \times 8.1 + (9.85 - 9.2) \times 9.5 = 104.475 \text{ kN/m}^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 1 + 0.49 \times 104.47 = 52.05 \text{ kN/m}^2$$

Block perimeter $\xi = 73.7 \text{ m}$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 73.7 \times 1.3 = 95.81 \text{ m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 52.05 \times 95.81 = 4986.48 \text{ kN}$$

- **Interacting Layer 3: [-10.5m] ↔ [-11.95m]**

Soil: Clay (Sandy Clay with Silt – SaClSi)

Effective column length in block/soil interaction zone $L_e = 1.45 \text{ m}$

$$\gamma_{sat} = 19.5 \text{ kN/m}^3 \quad \gamma_n = 18.7 \text{ kN/m}^3 \quad \gamma_w = 9.81 \text{ kN/m}^3 \quad \gamma' = 9.7 \text{ kN/m}^3$$

$$c' = 12 \text{ kPa} \quad \phi' = 20^\circ \quad OCR = 3$$

Since the soil layer is drained, the β method was used with effective parameters.

The β coefficient was calculated based on Equation (78).

$$\beta = (1 - \sin 20) \times 3^{0.5} \times \tan 20 = 0.41$$

Natural stresses were calculated at the center of the layer.

Total stress:

$$\begin{aligned} \sigma = & +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 \\ & + (10.5 - 9.2) \times 19.3 + (11.225 - 10.5) \times 19.5 = 206.128 \text{ kN/m}^2 \end{aligned}$$

Pore water pressure:

$$\begin{aligned} u_w = & +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 \\ & + (10.5 - 9.2) \times 9.81 + (11.225 - 10.5) \times 9.81 = 88.535 \text{ kN/m}^2 \end{aligned}$$

Effective stress:

$$\begin{aligned} \sigma' = & +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 \\ & + (10.5 - 9.2) \times 9.5 + (11.225 - 10.5) \times 9.7 = 117.682 \text{ kN/m}^2 \end{aligned}$$

Unit shaft resistance was obtained using Equation (77). Cohesion was considered.

$$f_s = 12 + 0.41 \times 117.68 = 60.81 \text{ kN/m}^2$$

Block perimeter $\xi = 73.7 \text{ m}$

Lateral surface area of the block:

$$A_s = \xi \times L_e = 73.7 \times 1.45 = 106.87 \text{ m}^2$$

Shaft resistance in the interaction layer was obtained by applying Equation (80).

$$Q_s = 60.81 \times 106.87 = 6498.99 \text{ kN}$$

• Total Shaft Resistance

Shaft resistances of all block/soil interaction layers are summed.

$$R_{s;k,gr} = \sum_{i=1}^3 Q_{si} = 15184.8 + 4986.48 + 6498.99 = \mathbf{26670.27 \text{ kN}}$$

Block Base Resistance

Effective shear strength angle at the block base: $\phi' = 20^\circ$

Elevation at the block base = -11.95m

Natural stresses at the block base have been calculated.

Total stress:

$$\sigma = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 19.4 + (9.2 - 2.8) \times 17.9 \\ + (10.5 - 9.2) \times 19.3 + (11.95 - 10.5) \times 19.5 = 220.265 \text{ kN/m}^2$$

Pore water pressure:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 \\ + (10.5 - 9.2) \times 9.81 + (11.95 - 10.5) \times 9.81 = 95.647 \text{ kN/m}^2$$

Effective stress:

$$\sigma' = +(2.2 - 0) \times 18.5 + (2.8 - 2.2) \times 9.6 + (9.2 - 2.8) \times 8.1 \\ + (10.5 - 9.2) \times 9.5 + (11.95 - 10.5) \times 9.7 = 124.715 \text{ kN/m}^2$$

Plastification angle $\psi_p = 0.4\pi$

Block base resistance was calculated for effective stresses using Equations (81), (82), and (83).

$$N_t = \left(\tan 20 + \sqrt{1 + \tan^2 20} \right)^2 e^{2 \times 0.4\pi \times \tan 20} = 5.091 \\ f_b = 5.091 \times 124.71 = 634.9 \text{ kN/m}^2$$

Block base area:

$$A_b = 337.3 \text{ m}^2$$

Base resistance:

$$R_{b;k,gr} = 634.9 \times 337.3 = \mathbf{214171.57 \text{ kN}}$$

Block Bearing Capacity

Self-weight of the rigid columns within the block:

$$W_{p,b} = n_p \times W_p = 99 \times 49.76 = 4926.52 \text{ kN}$$

Area of the soil enclosed within the block:

$$A_s = A_b - n_p \times \left(\frac{\pi \times D^2}{4} \right) = 337.3 - 99 \times \left(\frac{\pi \times 0.6^2}{4} \right) = 309.31 \text{ m}^2$$

Self-weight of the soil enclosed within the block:

$$W_{s,b} = \sum_1^{10} \gamma_{n,i} L_{e,i} A_s = 17 \times 5.25 \times 309.31 + 17.5 \times 1.3 \times 309.31 + 18.7 \times 1.45 \times 309.31 + = 931096.33kN$$

Self-weight of the block:

$$W_b = W_{p,b} + W_{s,b} = 4926.52 + 931096.33 = 47956.65kN$$

Pore water pressure at the block base:

$$u_w = +(2.8 - 2.2) \times 9.81 + (9.2 - 2.8) \times 9.81 + (10.5 - 9.2) \times 9.81 + (11.95 - 10.5) \times 9.81 = 95.647kN/m^2$$

The net self-weight of the block is determined by taking into account the pore water pressure at the base.

$$W_{b,net} = W_b - u_w \times A_b = 47956.65 - 95.65 \times 337.3 = 15694.27kN$$

Bearing capacity was obtained by applying Equation (62).

$$R_{c;k,gr} = R_{s;k,gr} + R_{b;k,gr} - W_b = 26670.27 + 214171.57 - 15694.27 = \mathbf{225147.56kN}$$

The group efficiency has been limited to 1 in order to remain on the safe side.

$$R_{c;k,gr} = n \times R_{c;k} = 99 \times 836.92 = 82855.3kN$$

Design of Rigid Column Group

Axial design load on the rigid column group: $F_{c;d,gr} = 35000kN$

Partial factor $\gamma_R = 1.5$

Design group bearing capacity:

$$R_{c;d,gr} = \frac{R_{c;k,gr}}{\gamma_R} = \frac{82855.3}{1.5} = \mathbf{55236.87kN}$$

$$F_{c;d,gr} = 35000kN/m^2 \leq R_{c;d} = 55236.87kN/m^2 \rightarrow \checkmark$$

Factor of safety:

$$FS = \frac{R_{c;k,gr}}{F_{c;d,gr}} = \frac{82855.3}{35000} = 2.37$$

21 “BLOCK F” Combined Bearing Capacity

The combined bearing capacity of the foundation system resting on rigid columns is being evaluated. The total capacity is obtained by combining the previously calculated shallow foundation bearing capacity with the bearing capacity of the rigid column group.

Combined bearing capacity:

$$q_{ult,comb} = q_{ult} + \frac{R_{c;k,gr}}{A} = 1599.68 + \frac{82855.3}{337.3} = \mathbf{1845.32kN/m^2}$$

Design combined bearing capacity:

$$q_{t,comb} = q_t + \frac{R_{c;d,gr}}{A} = 1142.63 + \frac{55236.87}{337.3} = \mathbf{1306.39kN/m^2}$$

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