UNIVERSITY OF RUHUNA

Faculty of Engineering

End-Semester 7 Examination in Engineering: May 2023

Module Number: CE7304 **Module Name: Geotechnical Engineering Design**

[Three Hours]

[Answer **all questions**, the marks associated with each question are indicated]

Q1. a) Briefly explain how piles can be categorized based on load transfer mechanism.

[1.5 Marks]

b) Subsurface profile at a proposed site for a compost production facility consists of a surficial medium dense sand deposit underlain by a stiff clay layer overlying a very dense sand deposit as shown in Figure Q1.1. A pile foundation consisting of precast concrete piles of 0.4 m x 0.4 m square cross section is suggested for the project. The piles are to be terminated at a depth of 9 m below existing ground surface. A series of laboratory tests had been conducted in association with the geotechnical field investigation at the site to obtain necessary engineering parameters for soil. The results are presented in Table Q1.1 with other design parameters. Perform design calculations required by following sections.

The below listed equations with usual notations may be useful in performing the calculations.

$Q_p = A_p q' N_q^* \leq A_p q_1$; where $q_1 = 50 N_q^* tan\varphi$

$\delta' = \varphi'$ and $K = (1 - \sin\varphi')$

$S_e = S_{e(1)} + S_{e(2)} + S_{e(3)}$

$S_{e(1)} = \frac{(Q_{wp} + \alpha_s Q_{ws})L}{A_p E_p}$, $S_{e(2)} = \frac{Q_{wp} C_p}{D q_p}$, and $S_{e(3)} = \frac{Q_{ws} C_s}{L q_p}$

$C_s = (0.93 + 0.16\sqrt{L/D})C_p$

Figure Q1.2, Figure Q1.3 and Figure Q1.4 may also be useful. The groundwater table at the site is located 1.0 m below the existing ground surface. The unit weight of water can be taken as 9.81 kN/m^3.

i) Estimate the ultimate axial load carrying capacity of a pile in compression and determine the structural load that can be allowed to be carried by the pile when an overall factor of safety of 2.5 is assumed.

[6.0 Marks]

ii) Estimate the total settlement of a pile that should be expected under the application of loading at the working state of the pile. Clearly state any assumptions that may be used in the calculations.

[4.0 Marks]

c) Given the magnitude of structural loads transferred via a certain set of columns at the proposed construction described in Section (b) are high, it is required to consider grouping of piles. Estimate the ultimate capacity of a group of precast piles arranged into a grid of 2 x 2 piles assuming 1.0 m grid spacing. The below listed equation with usual notations may be useful in performing the calculations.

$$\eta = 1 - \frac{\theta}{90}\left[\frac{(n-1)m+(m-1)n}{mn}\right]; \text{ where } \theta = tan^{-1}(D/s)$$

[2.0 Marks]

d) Pile load testing is often recommended to verify pile capacity estimates. In carrying out a pile load test, "it is important to take into account the time lapse after the end of pile driving". Explain the above statement with respect to testing of driven precast piles.

[1.5 Marks]

Q2. An indoor sports dome is to be constructed as a lightweight structure founded on shallow spread footings. Consider a rectangular footing of dimensions 1.5 m x 2 m loaded vertically with an eccentricity as shown in Figure Q2.1 to perform design calculations required by the following sections. The footing is to be founded at a depth of 1.0 m below ground surface. The subsurface ground profile at the site consists of a dense clayey sand layer of great thickness. The characteristic values of soil parameters are given in Table Q2.1. The groundwater table is located at great depth below the base of the footing.

a) Obtain the effective width and the effective length of the footing. With the use of usual notations, it is given that $e_L/L < 1/6$, $e_B/B < 1/6$, and the effective area, $A' = L_2B + \frac{1}{2}(B + B_2)(L - L_2)$. The parameters L_2 and B_2 can be obtained from Figure Q2.2.

[2.0 Marks]

b) Considering a limit state of *bearing resistance failure*, determine the design bearing resistance of the footing in accordance with the Design Approach 1-Combination 2 of the Eurocode 7 using Vesic's form of the general bearing capacity equation and the effective area method. Combinations of sets of partial factors $(A2 + M2 + R1)$ to be used with Design Approach 1 of Eurocode 7 are given in Table Q2.2, Table Q2.3, and Table Q2.4.
Following equations with usual notations may be used in the calculations.

The general bearing capacity equation:

$$q_u = c'N_cF_{cs}F_{cd}F_{ci} + qN_qF_{qs}F_{qd}F_{qi} + \frac{1}{2}\gamma BN_\gamma F_{\gamma s}F_{\gamma d}F_{\gamma i}$$

The bearing capacity factors N_c, N_q, and N_γ may be obtained from Table Q2.5.

F_{cs}, F_{qs}, and $F_{\gamma s}$ are the shape factors.

F_{cd}, F_{qd}, and $F_{\gamma d}$ are the depth factors.

F_{ci}, F_{qi}, and $F_{\gamma i}$ are the inclination factors

Shape factors

$$F_{cs} = 1 + \frac{B}{L}\frac{N_q}{N_c}$$

$$F_{qs} = 1 + \frac{B}{L}\tan\varphi'$$

$$F_{\gamma s} = 1 - 0.4\frac{B}{L}$$

Depth factors when $\frac{D_f}{B} \leq 1$

$$F_{cd} = F_{qd} - \frac{1 - F_{qd}}{N_c tan\varphi'}$$

$$F_{qd} = 1 + 2tan\varphi'(1 - sin\varphi')^2 \frac{D_f}{B}$$

$$F_{\gamma d} = 1$$

Depth factors when $\frac{D_f}{B} > 1$

$$F_{cd} = F_{qd} - \frac{1 - F_{qd}}{N_c tan\varphi'}$$

$$F_{qd} = 1 + 2tan\varphi'(1 - sin\varphi')^2 tan^{-1}\left(\frac{D_f}{B}\right)$$

$$F_{\gamma d} = 1$$

Inclination factors

$$F_{ci} = F_{qi} = \left(1 - \frac{\beta}{90^0}\right)^2$$

$$F_{\gamma i} = \left(1 - \frac{\beta}{\varphi'}\right)^2$$

β = inclination of the load on the foundation with respect to the vertical

[6.5 Marks]

c) Determine the design load that the footing can sustain.

[0.5 Marks]

d) Given the lightweight nature of the construction and the wind effect on the dome it also required to consider a limit state of *failure by sliding* at certain footing locations. For this design situation, consider that a permanent characteristic vertical load of 240 kN and a variable characteristic vertical load of 110 kN are transferred to the foundation soils via the footing in consideration.

   i) Determine the footing's design resistance to sliding (R_d) in accordance with the Design Approach 1-Combination 2 of the Eurocode 7. Combinations of sets of partial factors ($A2 + M2 + R1$) to be used with Design Approach 1 of Eurocode 7 are given in Table Q2.2, Table Q2.3, and Table Q2.4. Clearly state any assumptions that may be used in the calculations.

   [Note: Given the shallow depth of embedment of the footing, the effects of passive and active earth pressures on the sides of the footing may be ignored.]

[3.0 Marks]

ii) Explain how the design resistance to sliding (R_d) will be affected if the groundwater table in the area should rise above the foundation depth.

[3.0 Marks]

Q3. A sheet pile wall is proposed for canal bank protection over a stretch of canal running through an urban area. The retained height of medium dense clayey sand is 4.5 m. The normal water level in the canal and the groundwater table in the region remain 2.5 m below the retained surface of soil. A schematic drawing of the proposed wall system with the geometric parameters is provided in Figure Q3.1 together with the subsurface profile. The characteristic values of soil parameters are provided in Table Q3.1. The unit weight of water, γ_w may be taken as 9.81 kN/m³. The wall may be assumed to have a smooth surface resulting in 'zero' wall-soil interface friction. Adhesion between the wall and the soil may also be neglected.

Following equations with usual notations may be used in the calculations.

$$K_a = \frac{1-\sin\varphi'_d}{1+\sin\varphi'_d},\ K_p = \frac{1}{K_a}$$

a) Write expressions for effective vertical stress in regions above and below groundwater table within the retained mass of soil behind the wall. Then, write general expressions for the active state of effective horizontal stress in the regions.

[1.0 Marks]

b) Write an expression for effective vertical stress in soils beneath the canal bed. Then, write a general expression for the passive state of horizontal stress in the region.

[0.5 Marks]

c) Consider the possibility of a tension crack developing behind the wall and determine the depth of the tension crack.

[1.5 Marks]

d) Construct a diagram to illustrate lateral stress distribution on the wall and determine the force components that act on the wall. *[Note: Consider the possibility of the tension crack being filled with free water.]*

[5.5 Marks]

e) Using fixed earth support method check if the given depth of embedment of the sheet piles is adequate to prevent rotational failure of the wall.

[1.5 Marks]

Q4. a) A playground development project requires partial removal of a hill by making a cutting. The soil is stratified in the region. A firm silty clay layer extends to a depth of 5.0 m from the crest of the proposed cut-slope. This layer is underlain by a layer of stiff clay with sand which extends to depths well below the toe of the proposed cut-slope. Assuming *undrained behaviour* of soil, a preliminary assessment of the short-term stability of the cut-slope is to be carried out for the circular trial slip surface AD shown in Figure Q4.1. The design soil engineering parameters and the dimensional parameters are provided in Table Q4.1.

i) Considering the possibility of a tension crack developing near the crest of the slope as shown in Figure Q4.1, determine the depth of the tension crack.

[3.0 Marks]

ii) Estimate the destabilizing moment that tends to cause slip along the trial surface. *[Note: Consider the possibility of the tension crack being filled with free water. The unit weight of water, γ_w may be taken as 9.81 kN/m³.]*

[2.0 Marks]

iii) Approximating the angle θ_3 to be 7.5 degrees, estimate the resistance that develops in soil against slip along the trial surface AC. Hence, determine the factor of safety (F_s) against slip along the trial surface AC.

[3.0 Marks]

b) Considering *drained behavior* of soils, using a suitable sketch briefly describe the variation of stress conditions from initial state through end of construction to final state reached after dissipation of excess pore pressure in the shared region near the toe of the cut-slope and predict the change in factor of safety that shall be anticipated in the long-term.

[2.0 Marks]

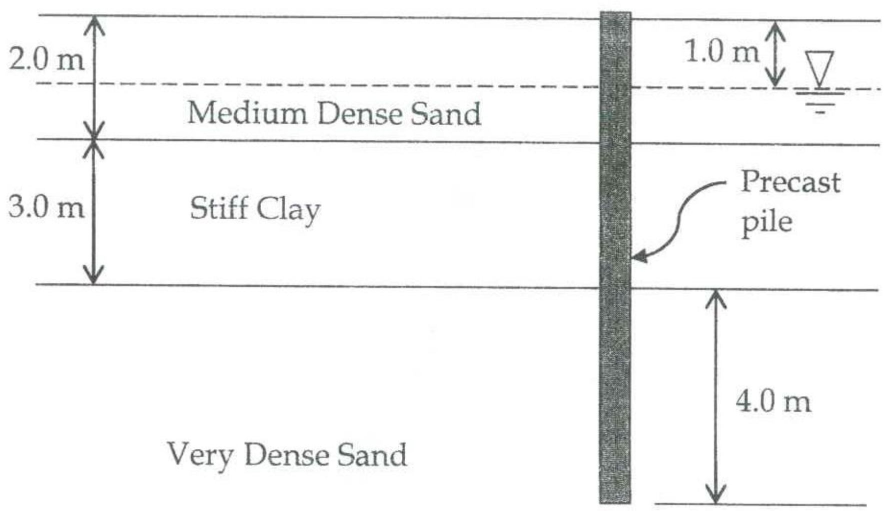

Figure Q1.1: Subsurface profile at the proposed site

Table Q1.1: Design parameters

Soil Parameters	Medium Dense Sand	Stiff Clay	Very Dense Sand
Drained cohesion, c' (kN/m^2)	0	10	0
Undrained cohesion, c_u (kN/m^2)	-	140	-
Friction Angle, φ' (deg)	30	25	38
Dry unit weight, γ_{dry} (kN/m^3)	18	-	-
Saturated unit weight (kN/m^3)	19	19.5	22
α_s = A factor that depends on the distribution of the unit frictional resistance, q_s along the pile shaft. The magnitude of α_s varies between 0.5 and 0.67.			
Modulus of elasticity of concrete (MPa) = 29580			

Typical values of C_p

Type of soil	Driven pile	Bored pile
Sand (dense to loose)	0.02-0.04	0.09-0.18
Clay (stiff to soft)	0.02-0.03	0.03-0.06
Silt (dense to loose)	003-0.05	0.09-0.12

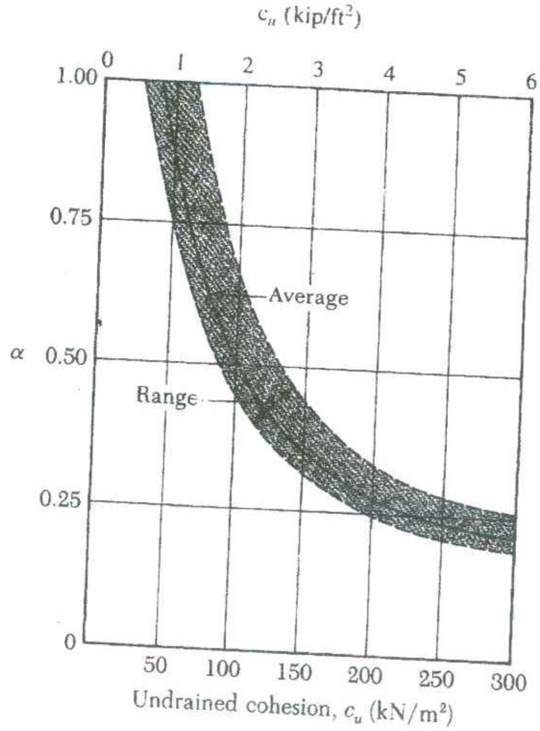

Figure Q1.2 - Variation of α with undrained cohesion of clay

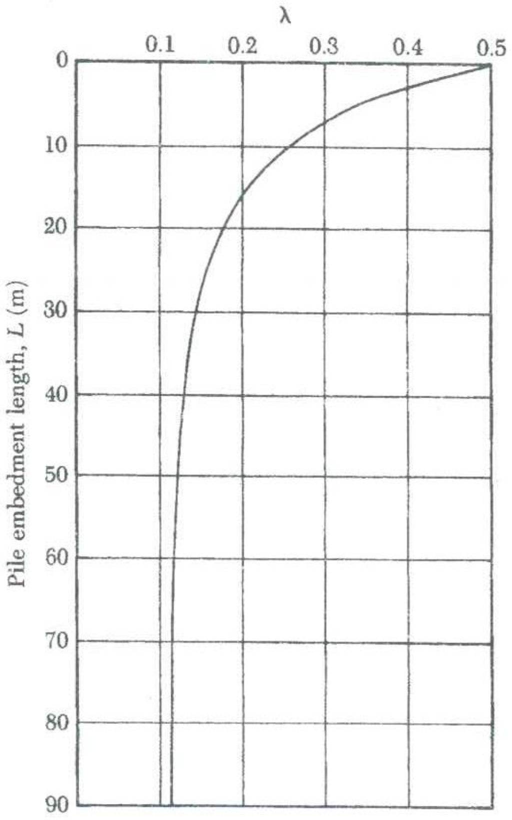

Figure Q1.3 - Variation of λ with pile embedded length

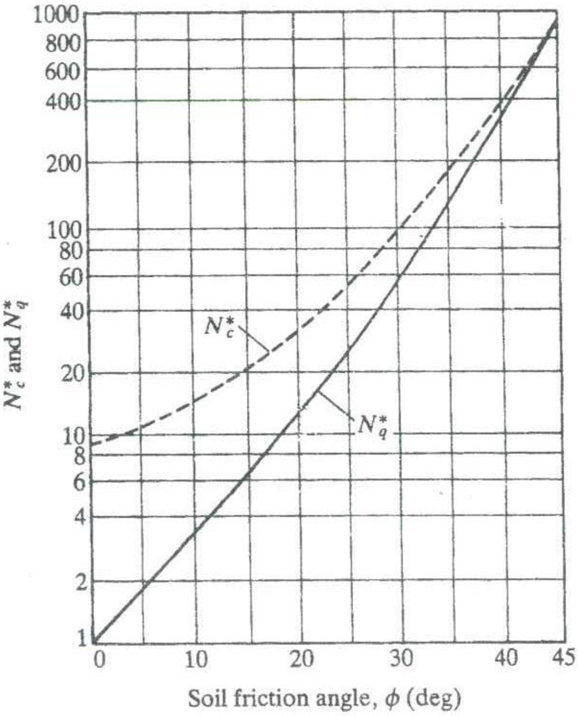

Figure Q1.4 - Variation of N_c^* and N_q^* with soil friction angle

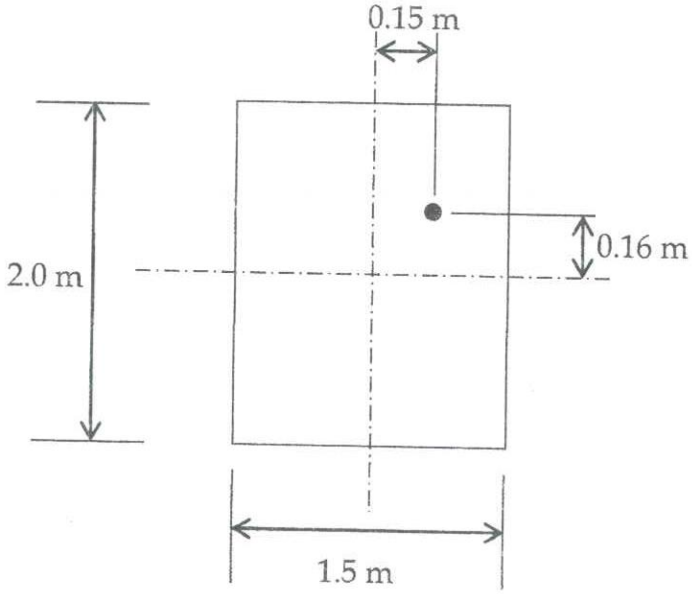

Figure Q2.1: Location of the column load with respect to footing

Table Q2.1: Characteristic values of soil parameters

Soil Parameters	Dense Clayey Sand
Dry unit weight, γ_{dry} (kN/m³)	19.5
Friction angle, φ' (deg)	32
Cohesion, c' (kN/m²)	10
Constrained Modulus, E_s' (MN/m²)	45
Footing-soil interface friction angle at the base, δ_{base}	$\delta_{base} = k.\varphi_{cv,d}$; $k = 1$ for footings cast against soil
Footing-soil interface adhesion at the base, a_{base}	0

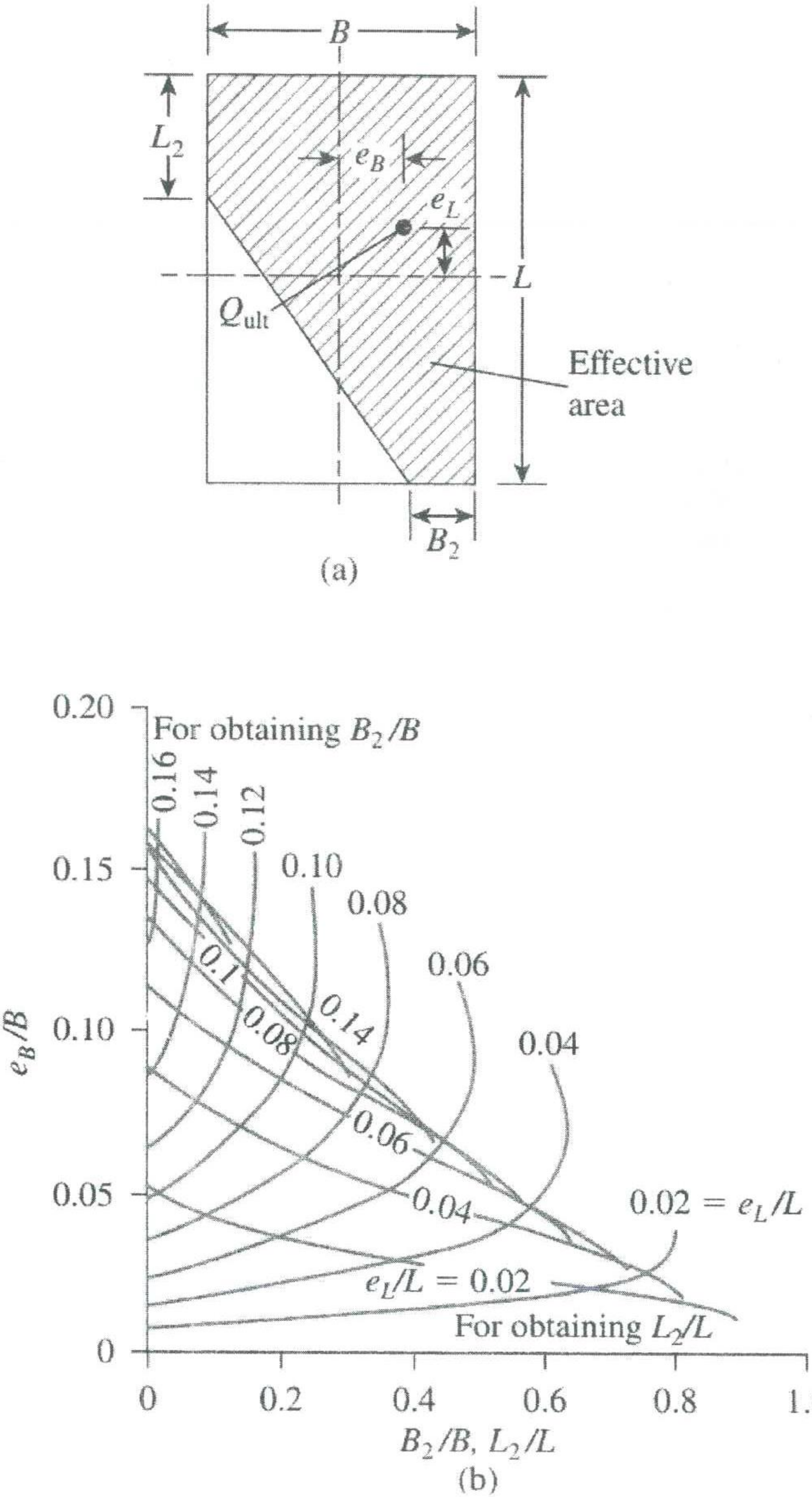

Figure Q2.2: The parameters L_2 and B_2 for determining effective dimensions of eccentrically loaded shallow footings

Table Q2.2: Partial factors on actions (γ_F) or the effects of actions (γ_E)

Action		Symbol	Set	
			A1	**A2**
Permanent	Unfavourable	γ_G	1.35	1.0
	Favourable		1.0	1.0
Variable	Unfavourable	γ_Q	1.5	1.3
	Favourable		0	0

Table Q2.3: Partial factors for soil parameters (γ_M)

Soil Parameter	**Symbol**	**Set**	
		M1	**M2**
Angle of shearing resistance [a]	$\gamma_{\varphi'}$	1.0	1.25
Effective cohesion	$\gamma_{c'}$	1.0	1.25
Undrained shear strength	γ_{cu}	1.0	1.4
Unconfined strength	γ_{qu}	1.0	1.4
Weight Density	γ_γ	1.0	1.0
[a] The factor is applied to $\tan\varphi'$			

Table Q2.4: Partial resistance factors (γ_R) for spread foundations

Resistance	**Symbol**	**Set**		
		R1	***R2***	***R3***
Bearing	$\gamma_{R,v}$	1.0	1.4	1.0
Sliding	$\gamma_{R,h}$	1.0	1.1	1.0

Table Q2.5: Vesic's Bearing Capacity Factors N_c, N_q, and N_γ

ϕ'	N_c	N_q	N_γ	ϕ'	N_c	N_q	N_γ
0	5.14	1.00	0.00	26	22.25	11.85	12.54
1	5.38	1.09	0.07	27	23.94	13.20	14.47
2	5.63	1.20	0.15	28	25.80	14.72	16.72
3	5.90	1.31	0.24	29	27.86	16.44	19.34
4	6.19	1.43	0.34	30	30.14	18.40	22.40
5	6.49	1.57	0.45	31	32.67	20.63	25.99
6	6.81	1.72	0.57	32	35.49	23.18	30.22
7	7.16	1.88	0.71	33	38.64	26.09	35.19
8	7.53	2.06	0.86	34	42.16	29.44	41.06
9	7.92	2.25	1.03	35	46.12	33.30	48.03
10	8.35	2.47	1.22	36	50.59	37.75	56.31
11	8.80	2.71	1.44	37	55.63	42.92	66.19
12	9.28	2.97	1.69	38	61.35	48.93	78.03
13	9.81	3.26	1.97	39	67.87	55.96	92.25
14	10.37	3.59	2.29	40	75.31	64.20	109.41
15	10.98	3.94	2.65	41	83.86	73.90	130.22
16	11.63	4.34	3.06	42	93.71	85.38	155.55
17	12.34	4.77	3.53	43	105.11	99.02	186.54
18	13.10	5.26	4.07	44	118.37	115.31	224.64
19	13.93	5.80	4.68	45	133.88	134.88	271.76
20	14.83	6.40	5.39	46	152.10	158.51	330.35
21	15.82	7.07	6.20	47	173.64	187.21	403.67
22	16.88	7.82	7.13	48	199.26	222.31	496.01
23	18.05	8.66	8.20	49	229.93	265.51	613.16
24	19.32	9.60	9.44	50	266.89	319.07	762.89
25	20.72	10.66	10.88				

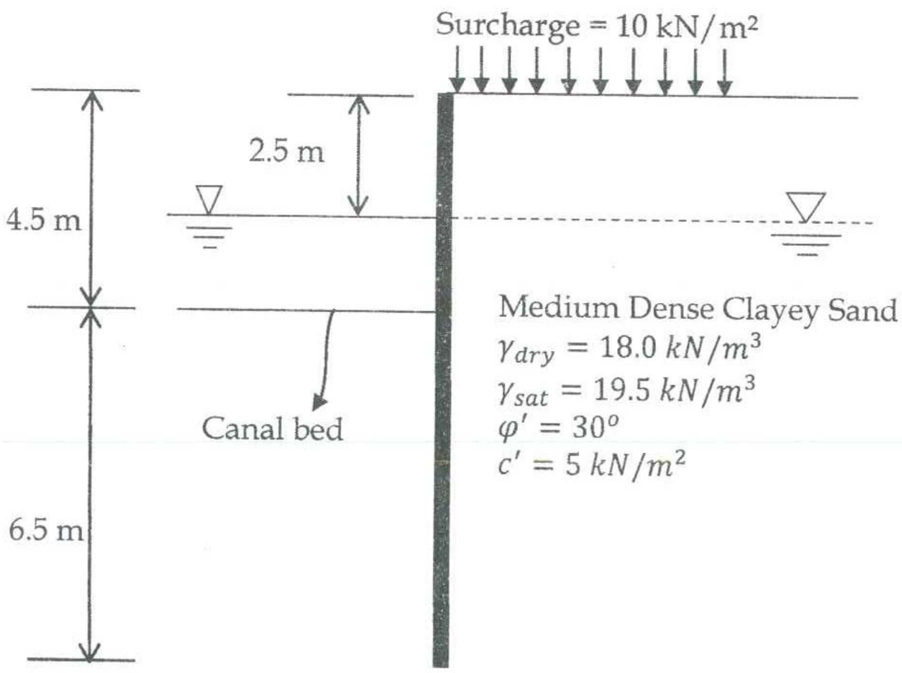

Figure Q3.1: Proposed sheet pile wall arrangement

Table Q3.1: Characteristic values of soil parameters

Soil Parameters	**Medium Dense Clayey Sand**
Dry unit weight, γ_{dry} (kN/m³)	18.0
Saturated unit weight, γ_{sat} (kN/m³)	19.5
Friction angle, φ' (deg)	30
Cohesion, c' (kN/m²)	5

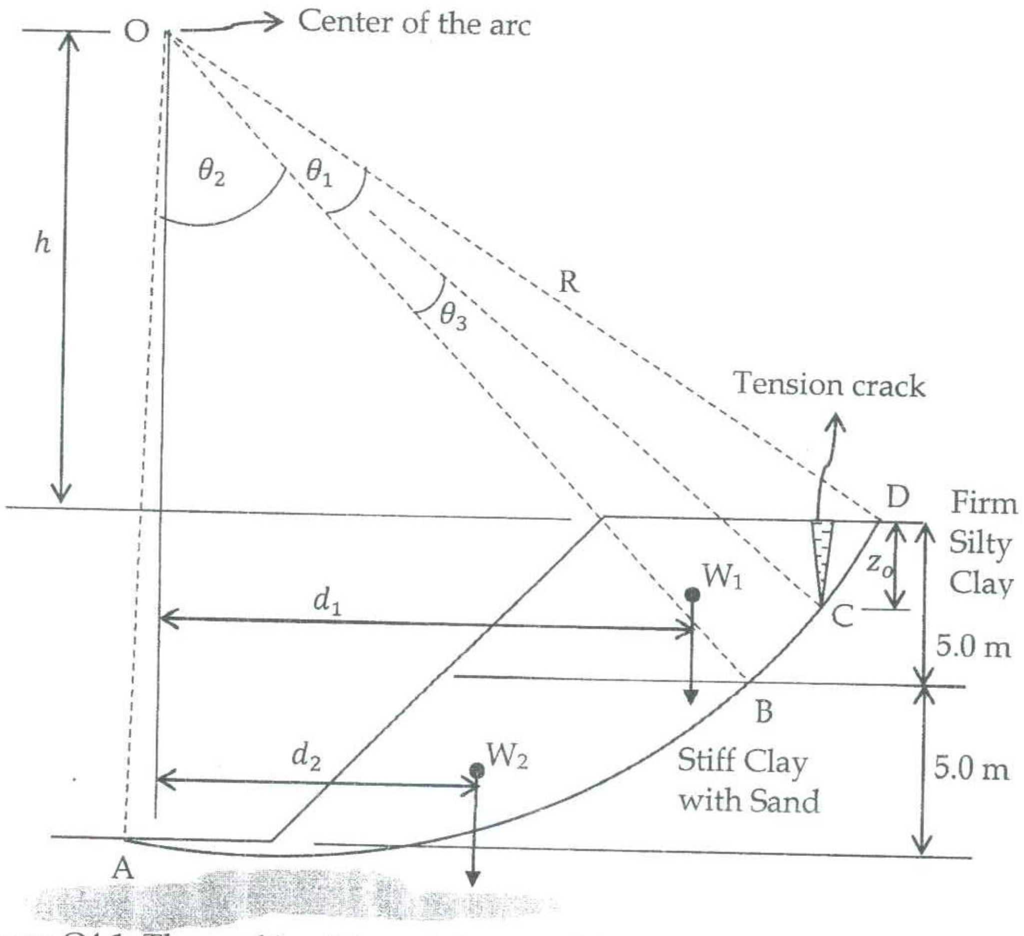

Figure Q4.1: The profile of the cut slope and the trial slip surface AD

Table Q4.1: Soil parameters and dimensional parameters

Soil Parameters	**Firm Silty Clay**	**Stiff Clay with Sand**
Undrained cohesion, c_u (kN/m²)	27	60
Saturated unit weight, γ_{sat} (kN/m³)	20.5	21.5
Dimensional parameters		
Radius of the trial slip surface AC, R (m)		20
Radial angle, θ_1 (degrees)		15
Radial angle, θ_2 (degrees)		45
Weight of potentially moving soil continuum, W_1 (kN/m)		412
Weight of potentially moving soil continuum, W_2 (kN/m)		308
d_1 (m)		12.5
d_2 (m)		7.0
h (m)		11.0