UNIVERSITY OF RUHUNA

Faculty of Engineering

End-Semester 7 Examination in Engineering: March 2021

Module Number: CE7305 **Module Name: Geotechnical Engineering Design**

[Three Hours]

[Answer **all questions**, each question carries **TWELVE** marks]

Q1. a) Explain two numbers of situations, other than the scenario presented in Section (c) below, where negative skin friction would develop on piles. You may use suitable sketches to support your answer.

[1.0 Marks]

b) Explain how downdrag force on piles that develop due to negative skin friction affects the overall design of a pile.

[2.0 Marks]

c) Subsurface profile at a proposed site for a multistory building consists of a surficial medium dense sand deposit underlain by a soft clay layer overlying a very dense sand deposit as shown in Figure Q1.1. Considering the presence of the clay layer, the structure is to be founded on piles. Precast piles of 0.5 m diameter are to be used for the purpose. The piles are to be terminated at a depth of 13 m below existing ground surface. A series of laboratory tests had been conducted in association with the geotechnical filed investigation at the site to obtain necessary soil engineering parameters and the results are presented in Table Q1.1. The groundwater table is located at the existing ground surface. The unit weight of water can be taken as 9.81 kN/m³. The below listed equations with general notations may be useful in performing the calculations required by following sections.

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

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

Figure Q1.2, Figure Q1.3 and Figure Q1.4 may be also useful in performing the calculations.

i) Estimate the total downdrag force that may develop on a pile caused by potentially ongoing consolidation of the clay layer. Clearly state any assumptions that may be used in the calculations.

[3.0 Marks]

ii) Estimate the ultimate axial load carrying capacity of a single pile. You may assume the following relationships with usual notations.
$\delta' = \varphi'$ and $K = (1 - \sin\varphi')$

[5.0 Marks]

iii) Given the magnitude of structural load transferred via a single column, it is required to consider a pile group consisting of four piles arranged into a 2 x 2 square grid. Estimate the ultimate capacity of the group assuming 1.0 m grid spacing.

[1.0 Marks]

Q2. A proposed school building is to be founded on shallow strip footings. Consider a strip footing of 1.5 m width (and 15 m length) loaded vertically along the longitudinal axis. The footing is to be founded at a depth of 1.0 m below ground surface. The subsurface ground profile at the site (as shown in Figure Q2.1) consists of a clayey sand overlying a normally consolidated (NC) clay layer. The clayey sand extends to a depth of 5 m below ground surface. The characteristic values of soil parameters are given in Table Q2.1. The groundwater table is located 1 m below the base of the footing and the unit weight of water can be taken as 9.81 kN/m^3.

a) 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. Clearly state any assumptions that may be used in the calculations.

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

[6.0 Marks]

b) In order to assess the footing under serviceability criteria, the settlements that occur due to the load effects need to be estimated. Based on the structural analysis the footing in concern is to be subjected to an unfactored load of 100 kN/m^2 applied at the foundation level. Under the application of this load perform a preliminary estimate of the immediate, consolidation, and total settlements using one-dimensional (1-D) settlement method. For the purpose of simplifying the calculations you may assume the footing to be placed at the existing ground level with the groundwater table also located at the existing ground level. The subsurface may be divided into n number of layers of thickness H_i = 1 m (where i = 1 to n) with the following equation with usual notations used to estimate the 1-D settlement. $S_{ID} = \sum\left(\frac{\Delta\sigma_{zi} H_i}{E'_{si}}\right)$

The vertical stress increment ($\Delta\sigma_z$) at a point beneath the center of an infinitely long strip of width B applying uniform vertical pressure of q at the ground surface can be determined using the illustration presented in Figure Q2.2. The calculations can be completed using Table Q2.5.

Note: The Table Q2.5 should be detached from the question paper and attached to the answer book.

[6.0 Marks]

Q3. a) Identify various uncertainties that require consideration in producing safe and functional geotechnical engineering designs.

[2.0 Marks]

b) Briefly describe the 'Plate Load Test' procedure.

[3.0 Marks]

c) Explain two numbers of situations where the plate load test can produce erroneous estimations of bearing capacity and settlement of shallow footings.

[1.0 Marks]

d) The subsurface profile encountered at a building site consists of a loose sand layer which extends to a depth of 4.0 m below ground surface. A plate load test was carried out in order to support the design of shallow footings for the project. The test was carried out using a 0.3 m diameter plate set at the center of a 2 m x 2 m pit excavated to a depth of 1 m. The results of the plate load test are shown in Figure Q3.1.

i) Using the test results estimate the ultimate bearing resistance of a 1 m x 1 m footing. The relationship between the ultimate bearing resistance of a footing in granular soil and that of the plate is given by the following equation with usual notations.

$$q_{u(F)} = q_{u(P)} \frac{B_F}{B_P}$$

[2.0 Marks]

ii) Given the settlement at a single column point is limited to a maximum of 20 mm under the serviceability criteria set for the project, reuse the plate load test data to determine the size of the square column footing that would carry a load of 100 kN. The following correlation between the settlement of a footing and the plate for a given intensity of load q_o applied to granular soils may be useful in the calculations.

$$S_F = S_P \left(\frac{2B_F}{B_F + B_P}\right)^2$$

[4.0 Marks]

Q4. a) Using a suitable sketch briefly describe the variation of factor of safety against slope instability from initial state through end of construction to final state reached after dissipation of excess pore pressure as relevant to construction of an embankment on saturated fine-grained soil.

[2.0 Marks]

b) Compare the 'Ordinary Method of Slices' (also termed the Swedish Circle Method or the Fellenius Method) with the Bishop's Simplified Method of Slices' for assessing slope stability.

[2.0 Marks]

c) A road construction project requires an embankment to be constructed. The preliminary assessment of stability of embankment slopes is to be carried out with the use of 'Bishop's Simplified Method of Slices'. Figure Q4.1 illustrates a section through the upstream slope profile and a trial slip surface AC. The design values of soil parameters for slope material are provided in Table Q4.1. The soil above the trial surface is divided into 7 vertical slices.

i) Using the Bishop's Simplified method of slices, find the factor of safety (F_s) against slip along the trial surface AC. Use an initial approximation of $F_s = 1.5$ and perform only one iteration. The calculation F_s can be completed using Table Q4.2. The following expression for F_s with usual notations may be used in the calculations assuming that the groundwater table is located at depth.

$$F_s = \frac{\sum_{n=1}^{n=p}(c'b_n + W_n \tan\varphi')\frac{1}{m_{\alpha(n)}}}{\sum_{n=1}^{n=p}(W_n \sin\alpha_n)}; \text{ where } m_{\alpha(n)} = \cos\alpha_n + \frac{\tan\varphi'}{F_s}\sin\alpha_n$$

Note: The Table Q4.2 should be detached from the question paper and attached to the answer book.

[6.0 Marks]

ii) After a prolonged rainy season, a rise in groundwater table can be considered such that the trial slip surface AC is intersected as shown in Figure Q4.2. Reflect on the principles underlying stability of slopes to explain how the elevated groundwater table would affect the stability of the slope in concern. You may use a suitable sketch to support your answer.

[2.0 Marks]

Q5. Construction of a gravity wall is proposed to retain a cut slope in clayey sand. The base width of the wall is 3.0 m and the retained height of backfill is 4.0 m. A schematic drawing of the proposed wall with the geometric parameters is provided in Figure Q5.1. The design groundwater table is located at a depth of 2 m below the base of the wall. The base of the wall is cast against soil. The wall may be assumed to have a 'smooth back' resulting in 'zero' wall-soil interface friction. The unit weight of concrete can be taken as 25 kN/m³. The characteristic values of soil parameters to be used in the design calculations are provided in Table Q5.1.

a) Perform the following design calculations 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 Q5.2, Table Q5.3, and Table Q5.4. Clearly state any assumptions that may be used in the calculations.

i) Construct a diagram to illustrate the lateral stress distribution on the wall and determine the force components that act on the wall.

[4.0 Marks]

ii) Check if the wall has adequate resistance against sliding at the base.

[3.0 Marks]

iii) Check if the wall has adequate stability against overturning.

[2.0 Marks]

iv) Determine the eccentricity of the vertical action (e) and check if the wall has satisfactory base width.

[1.0 Marks]

b) Due to inadequate provision for drainage, a temporary rise in groundwater table may be expected behind the wall after a prolonged rainy season, causing seepage at the base of the wall system. Explain how the design resistance to sliding at the base will be affected by this scenario. You may use a suitable sketch to support your answer.

[2.0 Marks]

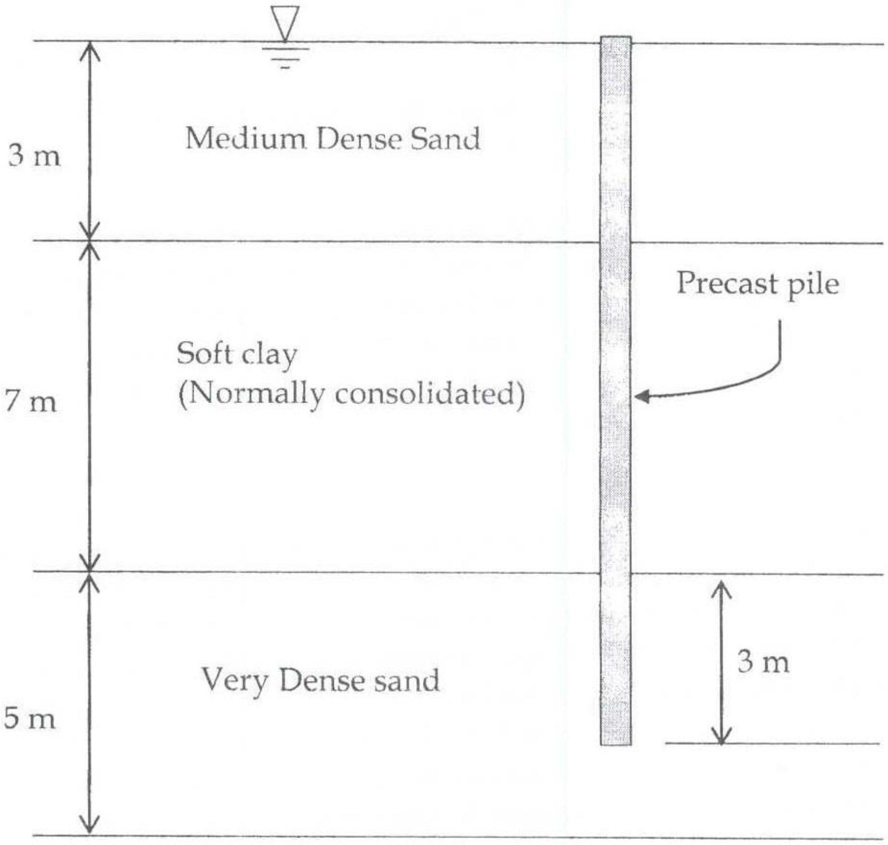


Figure Q1.1: Subsurface profile at the proposed site

Table Q1.1: Soil engineering parameters

Soil parameters	Medium Dense sand	Soft clay	Very Dense sand
Drained cohesion, c' (kN/m^2)	0	5	0
Undrained cohesion, c_u (kN/m^2)	0	30	0
Friction Angle, φ' (deg)	30	18	36
Saturated unit weight (kN/m^3)	19	16	21

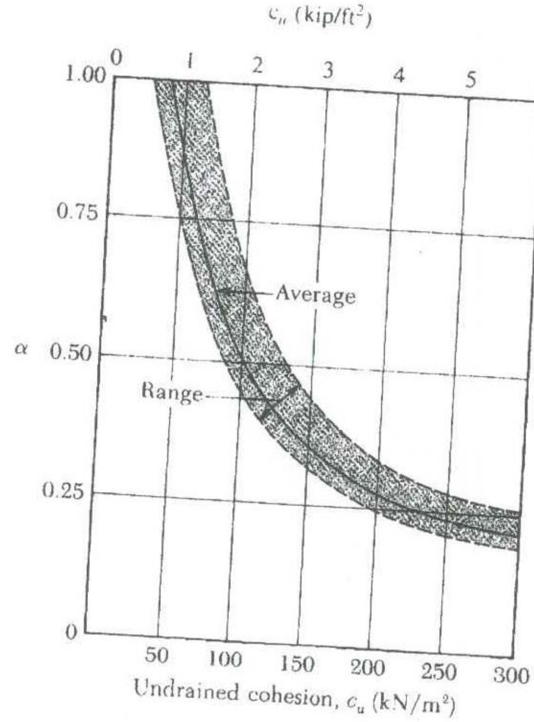


Figure Q1.2 - Variation of α with undrained cohesion of clay

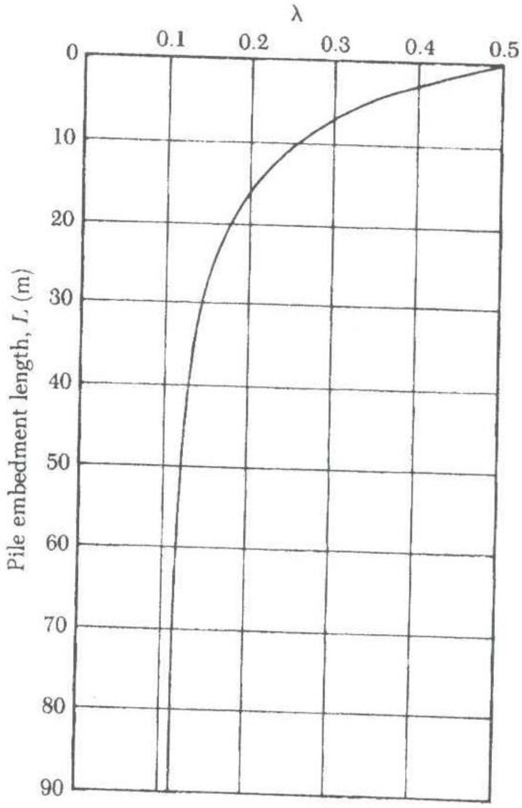


Figure Q1.3 - Variation of λ with pile embedded length

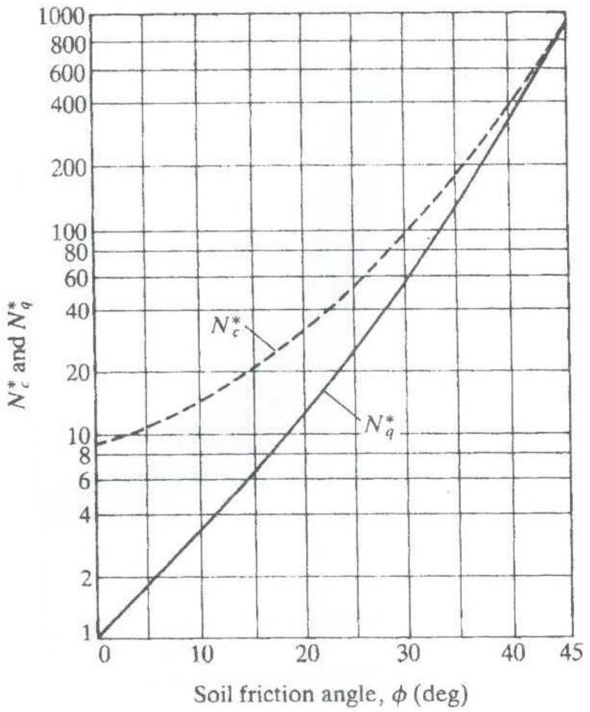


Figure Q1.4 - Variation of N_c^* and N_q^* with soil friction angle

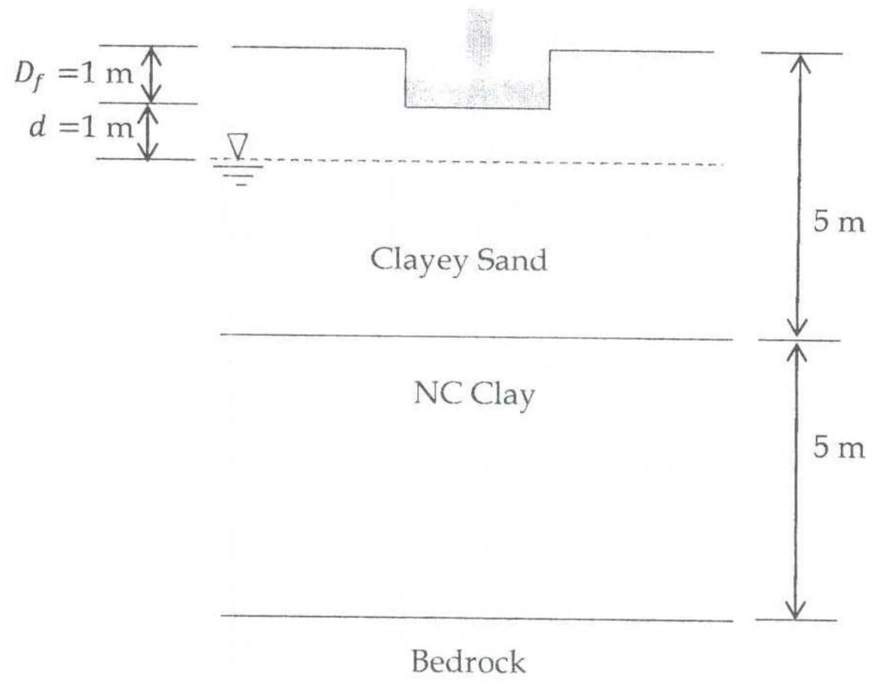


Figure Q2.1: Subsurface profile at the site

Table Q2.1: Characteristic values of soil parameters

Soil parameters	Clayey Sand	NC Clay
Dry unit weight, γ_{dry} (kN/m³)	18	19
Saturated unit weight, γ_{sat} (kN/m³)	20	20.5
Friction angle, φ' (deg)	30	25
Cohesion, c' (kN/m²)	5	15
Constrained Modulus, E_s' (MN/m²)	17	8

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)

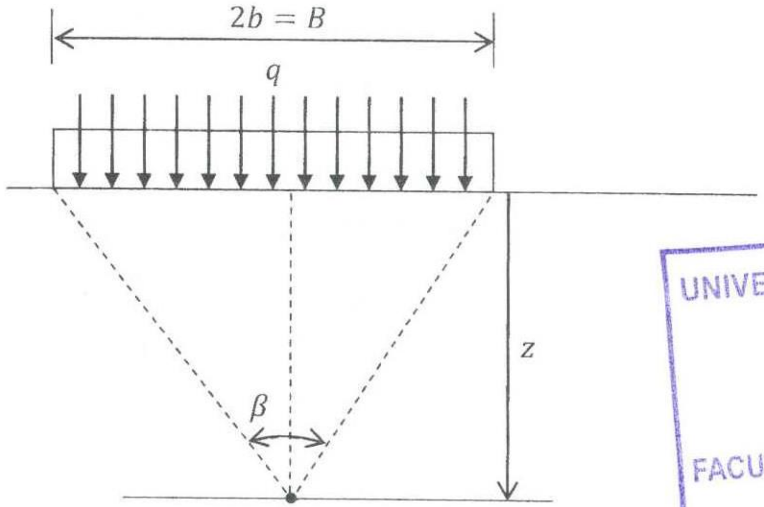
Soil Parameter	Symbol	Set	
		M1	M2
Angle of shearing resistance [a]	$\gamma_{\varphi'}$	1.0	1.25
Effective cohesion	$\gamma_{c'}$	1.0	1.25
Undrained shear strength	γ_{cu}	1.0	1.4
Unconfined strength	γ_{qu}	1.0	1.4
Weight Density	γ_{γ}	1.0	1.0
[a] The factor is applied to tan φ'			

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

Resitance	Symbol	Set		
		*R*1	*R*2	*R*3
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				



$$\Delta\sigma_Z = \frac{q}{\pi}[\beta + \sin\beta]; \text{ where } \beta = 2\tan^{-1}\left(\frac{B}{2Z}\right)$$

Figure Q2.2: Vertical stress increment ($\Delta\sigma_z$) at a point beneath the center of an infinitely long strip

Table Q2.5: Estimation of settlements beneath a strip footing

Layer No.	Thickness (m)	Mid depth, z (m)	β (rad)									
1	1	0.5										
2	1	1.5										
3	1	2.5										
4	1	3.5										
5	1	4.5										
6	1	5.5										
7	1	6.5										
8	1	7.5										
9	1	8.5										
10	1	9.5										

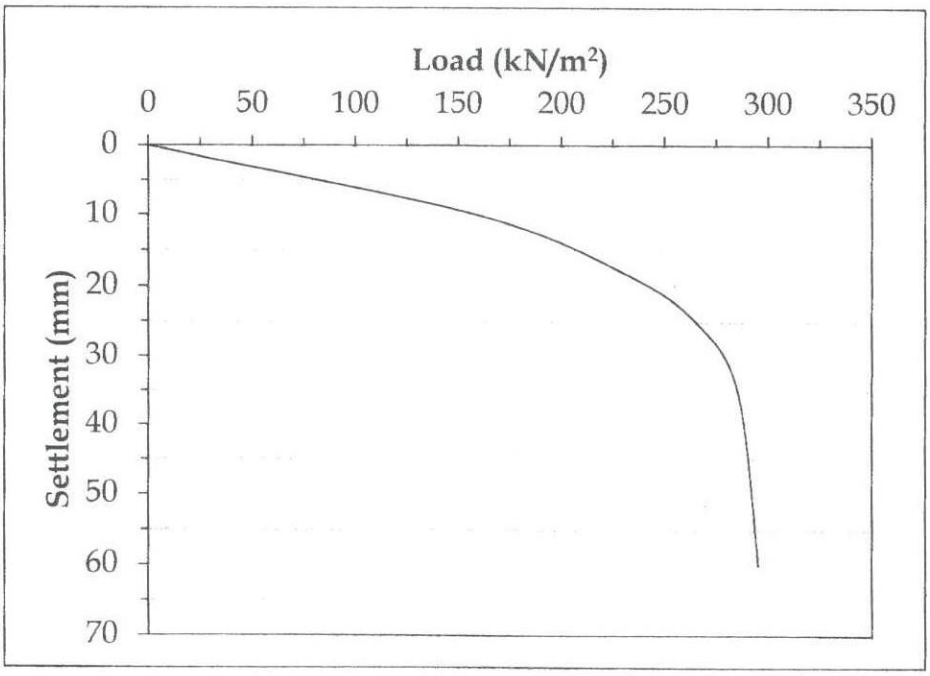


Figure Q3.1: Plate load test results

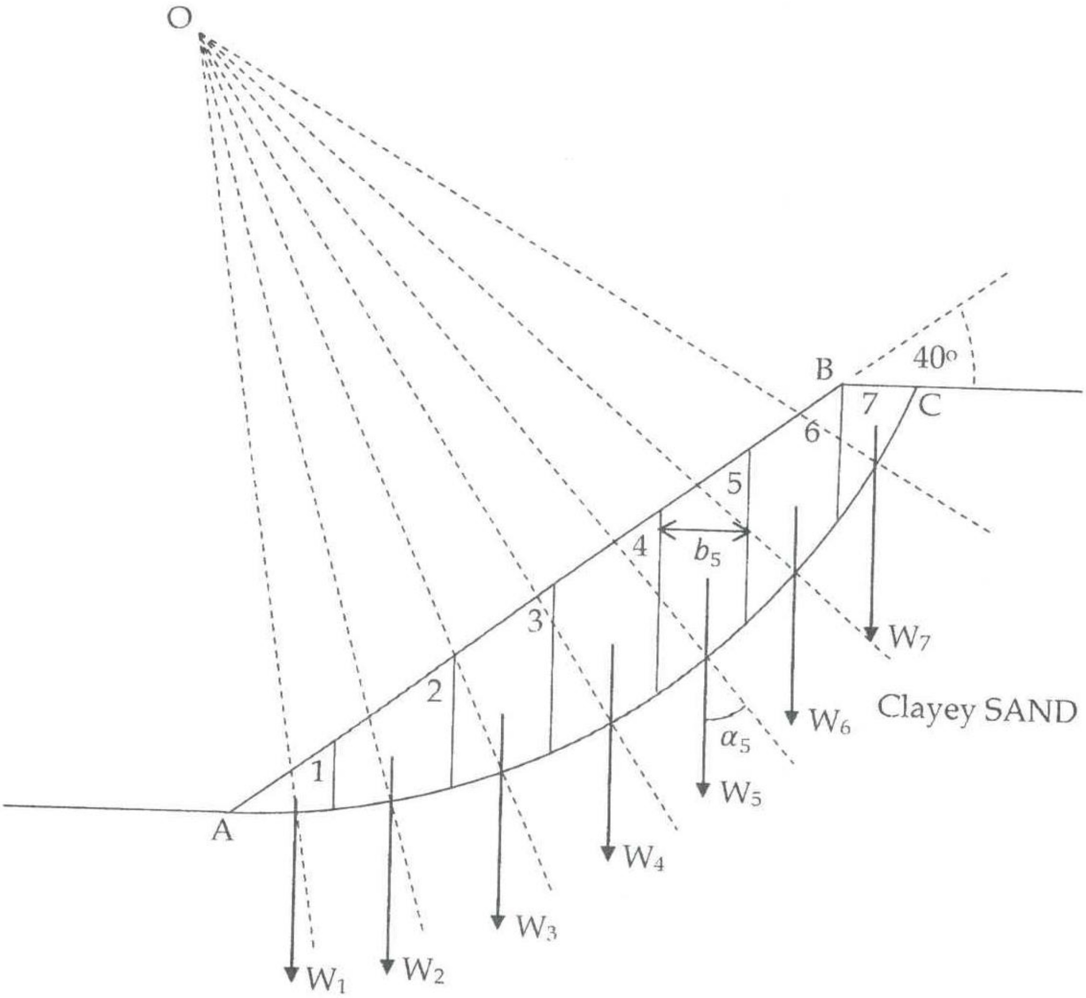


Figure Q4.1: The profile of the downstream slope and the trial slip surface AC

Table Q4.1: Soil parameters

Soil Parameters	Clayey Sand
Dry unit weight, γ_{dry} (kN/m³)	17.5
Friction angle, φ' (deg)	27
Cohesion, c′ (kN/m²)	15

Table Q4.2: Estimation of factor of safety against slip along the trial slip surface AC

Slice No.	W (kN/m)	α_n (deg)	b_n (m)						
1	29.8	10	1.3						
2	78.8	15	2.2						
3	105.0	33	2.0						
4	126.0	40	2.0						
5	113.3	47	1.8						
6	101.1	52	1.8						
7	29.4	63	1.3						

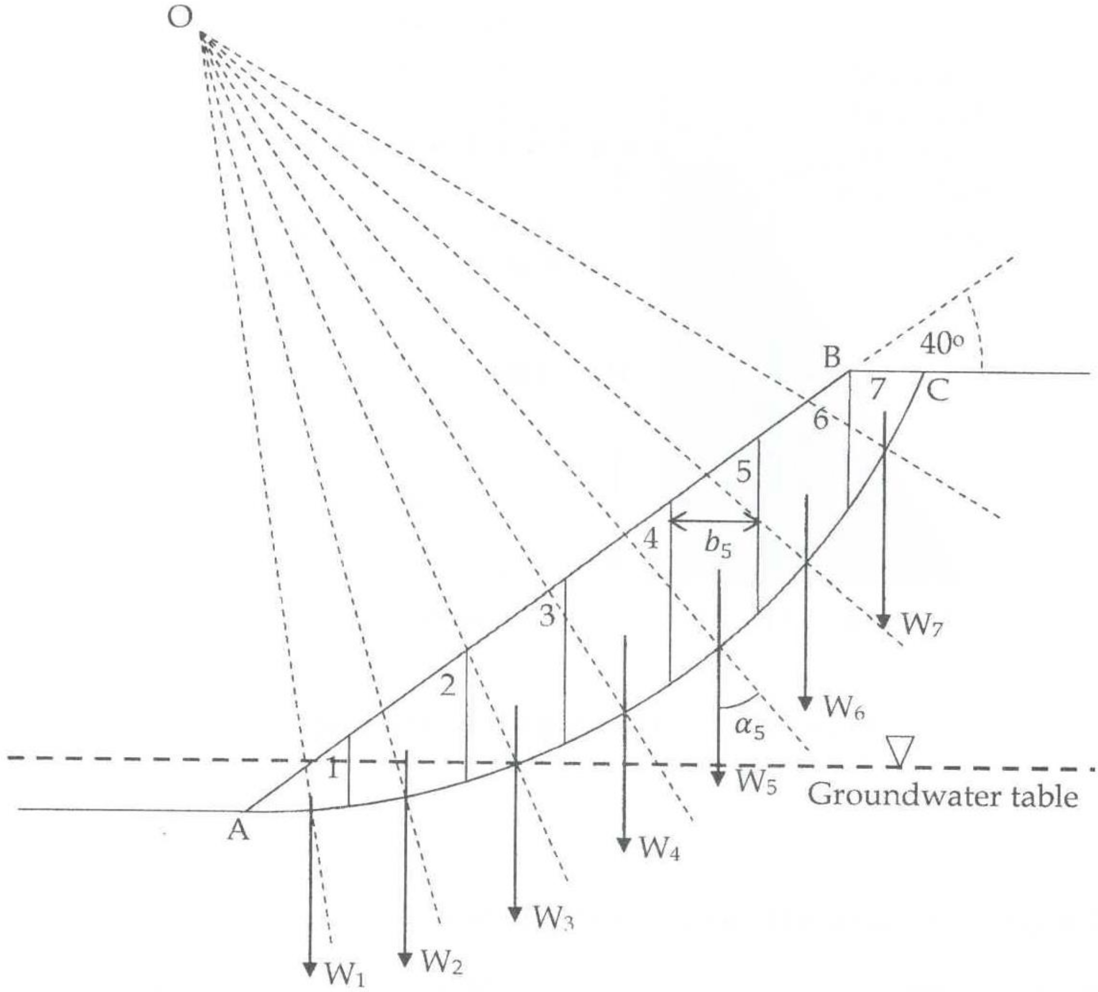


Figure Q4.2: The trial slip surface AC intersected by the groundwater profile

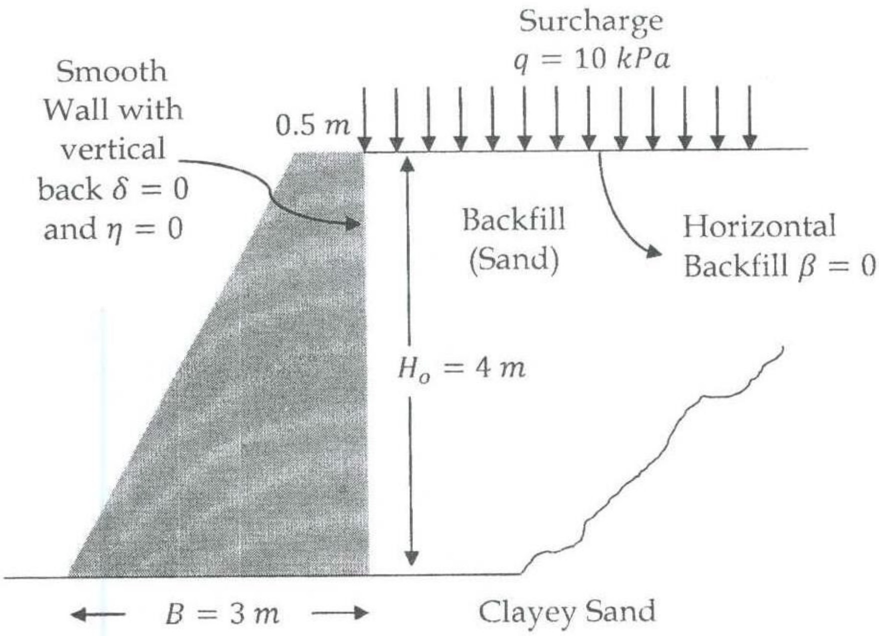


Figure Q5.1: Proposed gravity retaining wall

Table Q5.1: Characteristic values of soil parameters

Soil Properties	Backfill (Sand)	Clayey Sand
Dry unit weight, γ_{dry} (kN/m^3)	18	20
Friction angle, φ' (deg)	32	30
Cohesion, c' (kN/m^2)	0	8

Table Q5.2: 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 Q5.3: 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 φ'			

Table Q5.4: Partial resistance factors (γ_R) for retaining structures

Resitance	Symbol	Set		
		$R1$	$R2$	$R3$
Bearing capacity	$\gamma_{R,v}$	1.0	1.4	1.0
Sliding resistance	$\gamma_{R,h}$	1.0	1.1	1.0
Earth resistance	$\gamma_{R,e}$	1.0	1.4	1.0