THIS EXAMINATION CONSISTS OF **13** PAGES (INCLUDING THIS PAGE).
PLEASE CHECK THAT IT IS COMPLETE.

# THE UNIVERSITY OF BRITISH COLUMBIA

**Department of Civil Engineering**

## FINAL EXAMINATION – DECEMBER 2011
## SOIL MECHANICS II - CIVL 311

**Instructors: Dr. D. Wijewickreme and Dr. J.A. Howie**

Time: 3 hours

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1. **Closed Book** Examination; a calculator only is permitted.
2. Please ensure that you write your name and student number on the first page of all answer books.
3. Answer all 4 questions.
4. The formula sheet is attached.
5. Assume the unit weight of water to be 9.8 kN/m$^3$.
6. Make any reasonable assumptions (where appropriate and if required) to answer the questions.
7. Use sketches whenever possible.
8. Write clearly. Be neat and brief. Marks will be deducted for poor presentation.
9. Show all steps of your calculation to receive full marks.
10. Note the mark value distribution for each question.
11. Please return this exam paper at the end of the exam.
12. POSSIBLE MAXIMUM MARKS FOR THIS QUESTION PAPER = 120

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*Marks* **Question 1**

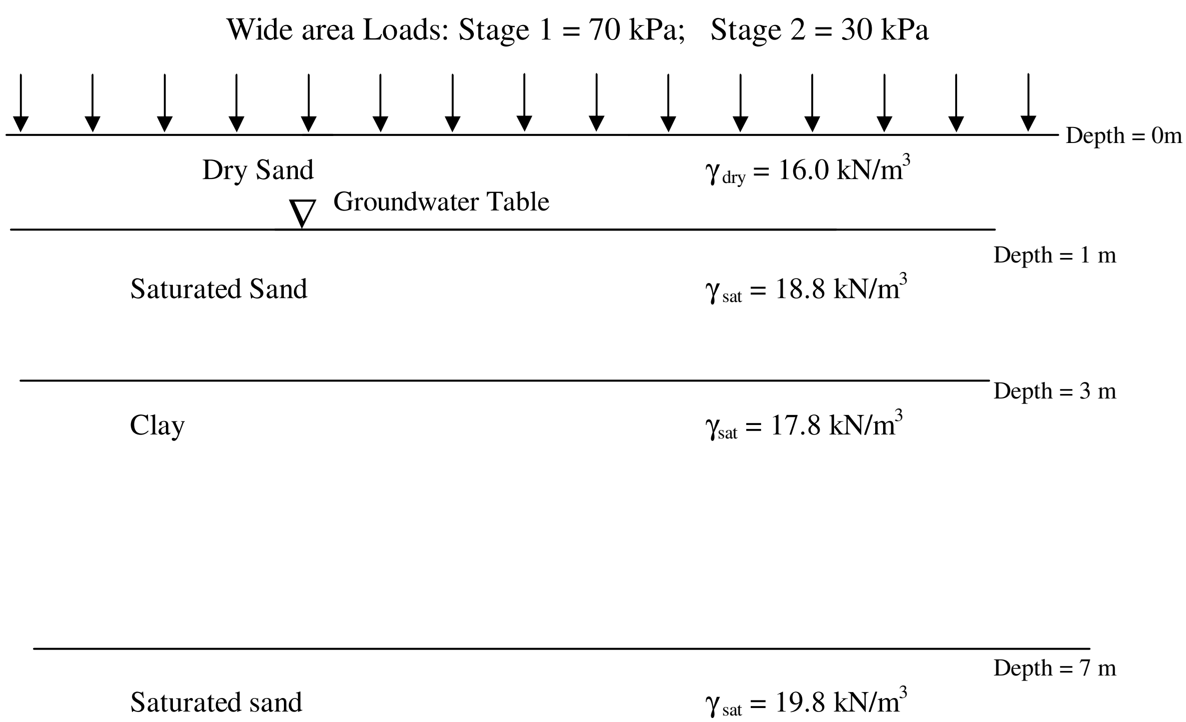
The soil stratigraphy at a site for a proposed industrial development is shown in the figure below (Note: Schematic diagram only. Not to scale.) The void ratio (e) versus vertical effective stress ($\sigma'_z$) curve given in Figure Q.1 (see page 13) was derived from a 1-dimensional consolidation test conducted on an undisturbed sample of the clay retrieved from the mid-depth of the clay deposit at this site. It has been suggested that placement of permanent wide-area loads of 70 kPa (Stage 1) and 30 kPa (Stage 2) as shown in the figure should be considered for design purposes.

*(10)* (a) Using the e versus $\sigma'_z$ relationship shown in Figure Q.1, determine the following parameters corresponding to the mid-depth of the clay deposit: (i) the in situ void ratio ($e_o$); (ii) preconsolidation pressure ($\sigma'_c$); (iii) overconsolidation ratio (OCR); (iv) Compression index ($C_c$); (v) Recompression index ($C_r$).

*(8)* (b) Assuming that the 1-D compression curve determined for the mid-depth of the clay deposit is representative of the entire clay layer, compute the expected primary consolidation settlement within the clay deposit due to the placement of the Stage 1 wide-area load of 70 kPa (ignore settlements within sand);

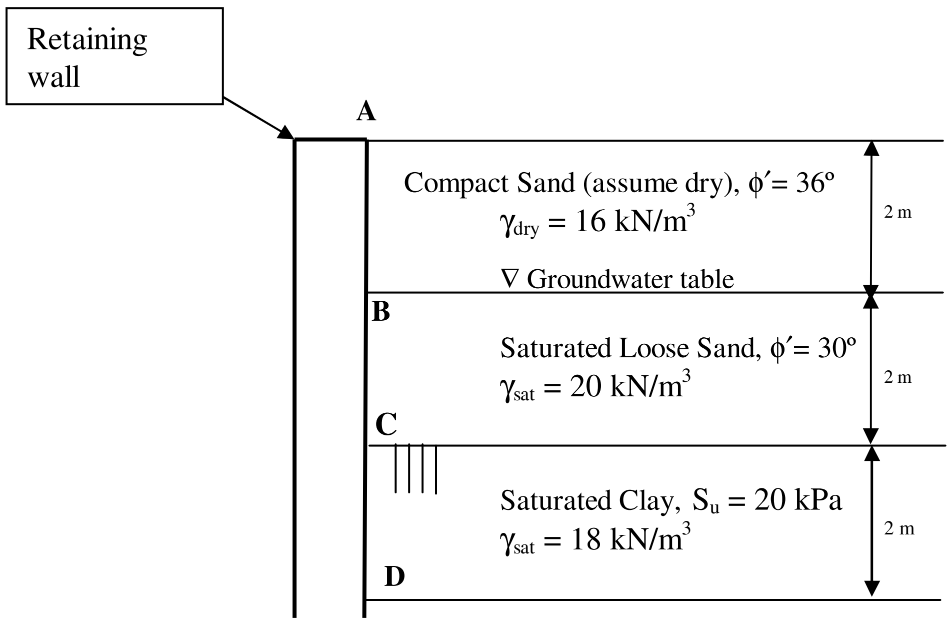
*(8)* (c) The Stage 2 wide area load of 30 kPa is to be applied well after completion of the primary consolidation settlement due to Stage 1 load. Again, assuming that the consolidation characteristics at the mid-depth of the clay deposit is representative of the entire clay layer, compute the expected primary consolidation settlement of the clay deposit due to the Stage 2 wide-area load of 30 kPa (ignore settlements within sand; assume that any secondary compression settlements due to the application of the Stage 1 wide-area load are negligible);

*(4)* (d) Estimate the time required for completion of 90% of total consolidation settlement due to the application of the Stage 2 wide area load (assume that wide-area load is placed relatively quickly and that the average coefficient of consolidation ($C_v$ ) for the clay layer is 3.2 x $10^{-3}$ $cm^2$/sec);



## Question 2

*(20)* (a) The design concept for an earth retaining structure is presented in the figure below. The soil and groundwater conditions assumed for the design is also shown. Estimate the lateral pressure distribution on the wall face ABCD considering active backfill soil conditions (i.e., need to compute and draw lateral pressures arising from both the soil and water pressures). Assume a smooth wall and static groundwater conditions (i.e., no groundwater flow), and use Rankine theory for the computations.



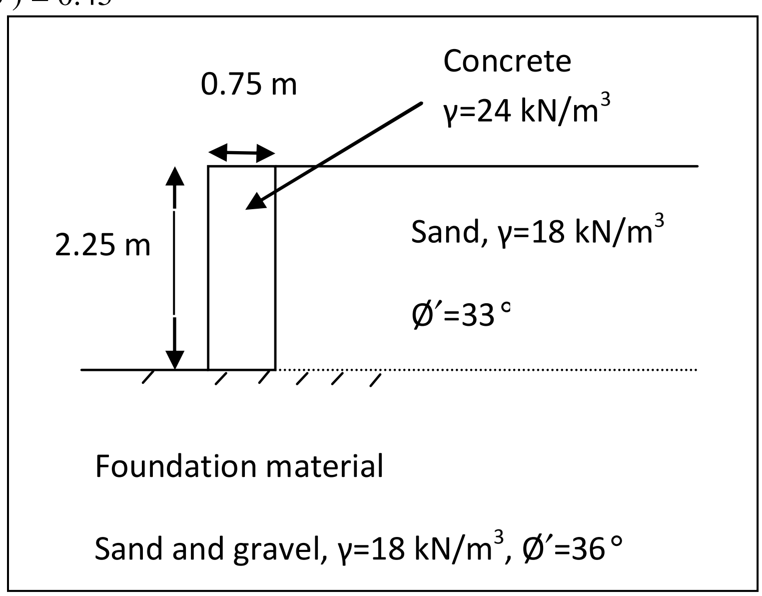

NOTE: Not to scale; schematic diagram only.

*(20)* (b) For the following calculations, assume Rankine active conditions. Assume that the backfill is well-drained and that the coefficient of friction between the concrete base of the wall and the foundation material is $\tan(0.67\phi') = 0.45$

(i) Calculate the factor of safety against sliding for the retaining wall shown.

(ii) Calculate the factor of safety against overturning for the retaining wall shown.

(iii) If the drainage system became blocked and water rose to be level with the top of the wall, calculate the new active force and the water force acting on the back of the wall (assume $\gamma$ remains unchanged after saturation).



## Question 3

*(10)* (a) Given the following information, compute the ultimate net bearing capacity of a 2.0 m square footing founded on a sand and gravel deposit.

(i) Peak friction angle: $\phi'_p = 36°$;
(ii) Depth of footing base below ground surface = $D_f$ = 1.0 m;
(iii) Groundwater table is located 1.0 m below ground surface;
(iv) Total unit weight of sand above groundwater level = 17.8 kN/m$^3$
(v) Total unit weight of sand below groundwater level $\gamma_{sat}$= 20.8 kN/m$^3$

*(10)* (b) A rectangular footing, 1 m x 2 m in plan dimensions, is to be founded on a clay deposit. The depth of footing embedment is 0.60 m, and the soil has a total (saturated) unit weight of 18 kN/m$^3$. Based on data from a geotechnical investigation, it has been determined that an undrained shear strength of 40 kPa would be suitable for design calculations. Determine the ultimate net bearing capacity of the foundation.

## Question 4

*(15)* (a) A closed-ended steel pipe pile (i.e., closed-ended cylindrical steel pile) having a diameter of 0.6 m is driven to a depth of 15 m into homogeneous normally consolidated clay. Given the following information, estimate the allowable short-term pile load capacity assuming a factor of safety of 3.0. Ignore weight of pile.

(i) Average soil parameters for the clay deposit: $S_u$ (remoulded) = 35 kPa; $\gamma_{sat}$= 17.8 kN/m$^3$;
(ii) Groundwater table is located at the ground surface; and
(iii) Assume that shaft frictional stress ($f_s$) computed considering vertical effective stress ($\sigma'_{z0}$) at mid length of pile can be considered applicable for the full length.

*(15)* (b) A timber pile having an average diameter of 0.33 m (i.e., ignore tapering of timber pile) is driven to a depth of 12 m into saturated sand deposit. Given the following information, estimate the allowable pile load capacity assuming a factor of safety of 3.0. Ignore weight of pile.

(i) Soil parameters for sand: Critical state friction angle ($\phi'_{cs}$) = 32º; interface friction angle ($\delta$) at the timber-sand interface = 27º; and $\gamma_{sat}$= 18.8 kN/m$^3$;
(ii) Groundwater table is located at the ground surface; and
(iii) Assume that shaft frictional stress $\beta$ ($\sigma'_z$) computed considering vertical effective stress ($\sigma'_z$) at mid length of pile can be considered applicable for the full length.

## EQUATION SHEET

**Computation of static effective stresses in a soil mass**

$\sigma'_z = \Sigma \gamma_i h_i$ ; $\sigma' = \sigma - u$ ;
$\gamma_i$ = Bulk unit weight of i th layer of soil;
$h_i$ = Thickness of i th layer of soil;
$\sigma'_z$ = Vertical effective stress;
$\sigma' = \sigma - u$ ; u = Pore water pressure

Under static groundwater (no flow) conditions: $u = \gamma_w z$

Under seepage flow conditions:
Total Head = Pore water pressure Head + Elevation Head (neglecting velocity head)
$h_{total} = h_{pwp} + h_{elev}$
$h_{total} = (u/\gamma_w) + z_{above\text{-}datum}$
Hydraulic gradient between A and B = $i_{AB} = [(h_{total})_{at\ point\ A} - (h_{total})_{at\ point\ B}] / L_{AB}$
Where $L_{AB}$ = Distance between points A and B

**Consolidation Settlements**

For a given layer,
Consolidation settlement = $\rho_{pc} = \varepsilon_z . H_0$ where
$\varepsilon_z = [\Delta e / (1+e_o)]$;
$H_0$ = Initial thickness of the layer considered for calculating consolidation settlements;
$e_o$ = initial void ratio;
$\Delta e$ = change in void ratio;

Based on this, for normally consolidated soil,

$$\rho_{pc} = H_o \frac{\Delta e}{1+e_o} = \frac{H_o}{1+e_o} C_c \log \frac{\sigma'_{\text{fin}}}{\sigma'_{\text{zo}}}; \quad \text{OCR} = 1 \qquad (6.14)$$

$$\sigma'_{\text{fin}} = \sigma'_{zo} + \Delta\sigma_z$$

$\sigma'_{zo}$ = initial vertical effective stress; $\Delta\sigma_z$ = vertical stress increase
$\sigma'_{fin}$ = final vertical effective stress
$C_c$ = Compression index = $(e_2-e_1)/[\log(\sigma'_{z2} / \sigma'_{z1})]$ along normal consolidation line;

Based on this, for overconsolidated soil,

$$\rho_{pc} = \frac{H_o}{1+e_o} C_r \log \frac{\sigma'_{\text{fin}}}{\sigma'_{\text{zo}}}; \quad \sigma'_{\text{fin}} < \sigma'_{\text{zc}} \qquad (6.15)$$

$$\rho_{pc} = \frac{H_o}{1+e_o} \left( C_r \log \frac{\sigma'_{\text{zc}}}{\sigma'_{\text{zo}}} + C_c \log \frac{\sigma'_{\text{fin}}}{\sigma'_{\text{zc}}} \right); \quad \sigma'_{\text{fin}} > \sigma'_{\text{zc}} \qquad (6.16)$$

$C_r$ = Recompression index = $(e_2-e_1)/[\log(\sigma'_{z2} / \sigma'_{z1})]$ along recompression line;

**Rate of Consolidation**

$T_v$ = Time Factor
$H_{dr}$ = Drainage Path Length
$t_{90}$= Time for 90% degree of consolidation
$C_v$ = Coefficient of Consolidation

$$T_v = \frac{C_v t_{90}}{H_{dr}^{\,2}} = 0.848$$

$$T_v = \frac{\pi U^2}{4} \ for U < 0.6$$

Note: Degree of consolidation (U) is expressed as a decimal value in this equation.

**Lateral Earth Pressures**

(i) Effective stress analysis

Coefficient of active earth pressure = $K_a$
Effective lateral earth pressure under active conditions = $(\sigma'_x)_a$
Effective vertical stress at a given depth = $\sigma'_z$

$(\sigma_x')_a = K_a \sigma_z'$

$$\frac{(\sigma_x')_a}{(\sigma_z')} = \frac{1-\sin\phi'}{1+\sin\phi'} = K_a$$

Coefficient of passive earth pressure = $K_p$
Effective lateral earth pressure under passive conditions = $(\sigma'_x)_p$
Effective vertical stress at a given depth = $\sigma'_z$

$(\sigma_x')_p = K_p \sigma_z'$

$$\frac{(\sigma_x')_p}{(\sigma_z')} = \frac{1+\sin\phi'}{1-\sin\phi'} = K_p$$

(ii) Total stress analysis:

Active earth pressure = $(\sigma_x)_a$
Total vertical stress at a given depth = $\sigma_z$

$$(\sigma_x)_a = (\sigma_z) - 2S_u$$

Note: At tension crack depth level, $Z_{crack}$ below the ground surface, $(\sigma_x)_a = 0$.

Passive earth pressure = $(\sigma_x)_p$
Total vertical stress at a given depth = $\sigma_z$

$$(\sigma_x)_p = (\sigma_z) + 2S_u$$

**Bearing capacity of Shallow Foundations**

Effective Stress Analysis (ESA)

$$q_u = \gamma D_f (N_q - 1)(s_q d_q w_q) + 0.5\gamma B' N_\gamma (s_\gamma d_\gamma w_\gamma)$$

Total Stress Analysis (TSA)

$$q_u = 5.14 s_u (s_c d_c)$$

Definition of the factors to account for the different variations:

$s_q, s_\gamma, s_c$ - Shape of Footing

$d_q, d_\gamma, d_c$ - Depth of Footing Embedment

$w_q, w_\gamma$ - Groundwater level

$q_u$ - Net bearing capacity; $S_u$ - Undrained shear strength

$$N_q = e^{\pi \tan\phi'_p} \tan^2\left(45° + \frac{\phi'_p}{2}\right); \ \phi'_p \text{ in degrees}$$

Caquot and Kerisel (1953)[2]: $N_\gamma = 2(N_q + 1)\tan\phi'_p$; $\phi'_p$ in degrees

Meyerhof (1976): $N_\gamma = (N_q - 1)\tan(1.4\phi'_p)$; $\phi'_p$ in degrees

Davis and Booker (1971)[3] :

smooth foundation, $N_\gamma = 0.0663\exp(9.3\phi'_p)$; $\phi'_p$ in radians

rough foundation, $N_\gamma = 0.1054\exp(9.6\phi'_p)$; $\phi'_p$ in radians

Ueno et al. (1998)[4] :

rough foundation, $N_\gamma = 0.477\exp(6.52\phi'_p)$; $\phi'_p$ in radians

Note: Unless specifically stated otherwise, use Davis and Booker (1971) for rough foundations given above to determine $N_\gamma$.

## Effective Footing Dimensions

$$B' = B - 2e_B$$

$$L' = L - 2e_L$$

Definition of the factors to account for the different variations:

$s_q, s_\gamma, s_c$ - Shape of Footing

$d_q, d_\gamma, d_c$ - Depth of Footing Embedment

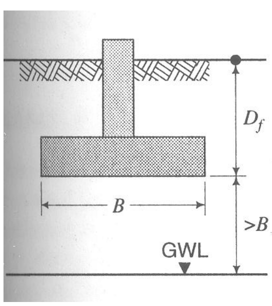
$w_q, w_\gamma$ - Groundwater level

$s_q = 1 + [(B'/L')*\tan\phi'_p]$; $s_\gamma = 1 - 0.4*(B'/L')$; $s_c = 1 + 0.2*(B'/L')$

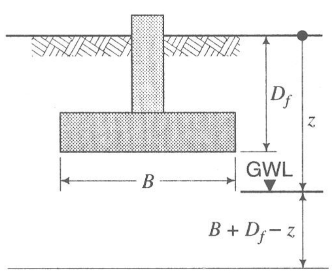
$d_q = 1 + [2*\tan\phi'_p]*(1-\sin\phi'_p)^2 * \tan^{-1}(D_f/B')$ for $(D_f/B') > 1$
$d_q = 1 + [2*\tan\phi'_p]*(1-\sin\phi'_p)^2 * (D_f/B')$ for $(D_f/B') \leq 1$

$d_\gamma = 1$

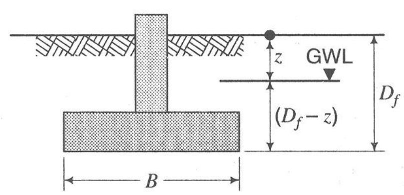
$d_c = 1 + [0.33*\tan^{-1}(D_f/B')]$ for $(D_f/B') > 1$
$d_c = 1 + [0.33*(D_f/B')]$ for $(D_f/B') \leq 1$




Case 1: $Z > (B+D_f)$




Case 2: $(B+D_f) > Z > D_f$




Case 3: $Z < D_f$

$$Case\_1: w_q = 1; w_\gamma = 1$$

$$Case\_2: w_q = 1; w_\gamma = \frac{(z - D_f)}{B} + \frac{\gamma'}{\gamma_{sat}}(1 + \frac{D_f}{B} - \frac{z}{B})$$

$$Case\_3: w_q = \frac{z}{D_f} + \frac{\gamma'}{\gamma_{sat}}(1 - \frac{z}{D_f}); w_\gamma = \frac{\gamma'}{\gamma_{sat}}$$

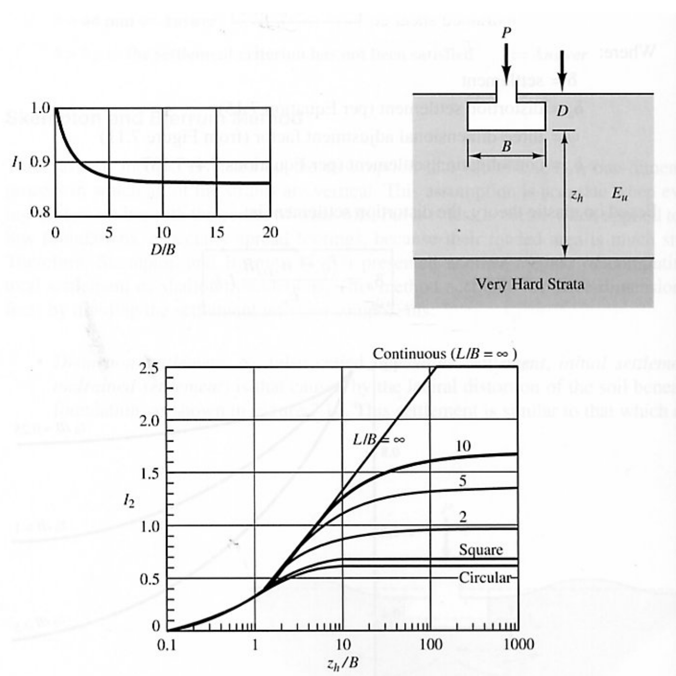
**<u>Estimation of settlements of foundations on clay</u>**

**(a) Distortion Settlements in clay**

$$\rho_e = \frac{(q - \sigma'_{zD})B}{E_u} I_1 I_2$$

Wher

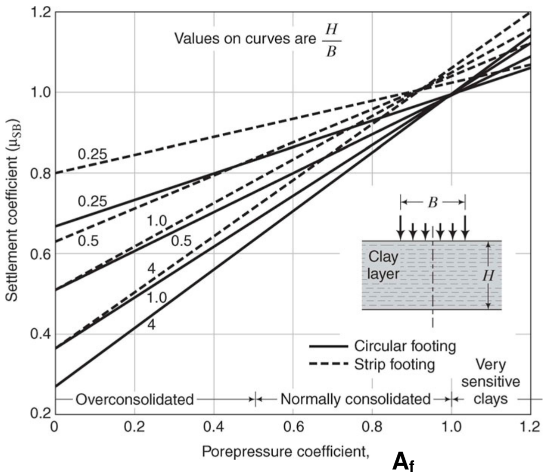
$\rho_e$ = distortion settlement
$q$ = bearing pressure
$\sigma_{zD}'$ = vertical effective stress at a depth $D$ below the ground surface
$B$ = foundation width
$I_1, I_2$ = influence factors (per Figure 7.12)
$E_u$ = undrained modulus of elasticity of soil



### (b) Consolidation Settlements in clay

Use formulae given in Page 1 to compute 1-D consolidation settlements.

Skempton Bjerrum correction factor.




$$\rho_{pc,3D} = \mu_{SB}\rho_{pc,1D}$$

### (c) Secondary compression settlements

$$C_a = -\frac{(e_t - e_p)}{\log(t/t_p)}; t > t_p \qquad \rho_{sc} = \frac{H_0}{(1+e_p)} C\alpha \log(t/t_p)$$

**<u>Estimation of settlements of foundations on sand</u>**

$$C_1 = 1 - 0.5\left(\frac{\sigma'_{zD}}{q - \sigma'_{zD}}\right)$$

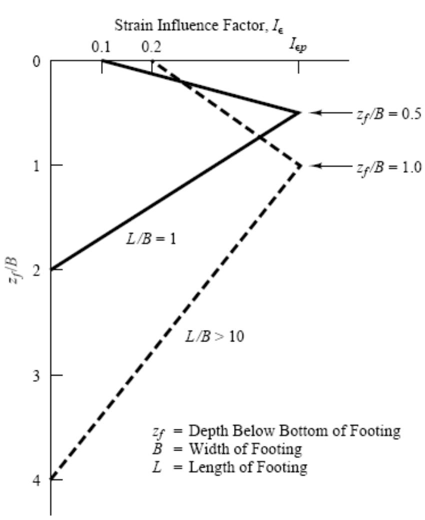
$$C_2 = 1 + 0.2\log\left(\frac{t}{0.1}\right)$$

$$C_3 = 1.03 - 0.03\,L/B \geq 0.73$$

$$\rho = C_1 C_2 C_3 (q - \sigma'_{zD}) \Sigma \frac{I_\varepsilon H}{E_s}$$

Where:

$\rho$ = settlement of footing
$C_1$ = depth factor
$C_2$ = secondary creep factor (see discussion in Section 7.8)
$C_3$ = shape factor = 1 for square and circular foundations
$q$ = bearing pressure
$\sigma_{zD}'$ = effective vertical stress at a depth $D$ below the ground surface
$I_\epsilon$ = influence factor at midpoint of soil layer
$H$ = thickness of soil layer
$E_s$ = equivalent modulus of elasticity in soil layer
$t$ = time since application of load (yr) ($t \geq 0.1$ yr)
$B$ = foundation width
$L$ = foundation length




Peak value of $I_\varepsilon = I_{\varepsilon p} = 0.5+0.1\sqrt{[(q-\sigma'_{zd})/\sigma'_{zp}]}$

$\sigma'_{zp}$ = value of vertical effective stress at $I_{\varepsilon p}$
$\sigma'_{zd}$ = vertical effective stress at foundation level; q = bearing pressure

**Load Capacity of Pile foundations**

**(a) Axial Pile Capacity - Static Pile Analysis**

$$Q_{ult} = Q_f + Q_b - W_p \qquad Q_a = \frac{Q_{ult}}{FS}$$

$Q_b >> Q_f$ End Bearing Pile; $Q_f >> Q_b$ Friction Pile

$Q_b$ = Ultimate End Bearing Resistance; $Q_f$ = Ultimate Shaft Frictional Resistance

$W_p$ = Weight of pile; FS = safety factor

**(b) Pile Capacity in fine-grained saturated soils**

**(b.1) Shaft Friction**

$Q_f = \Sigma\, (f_s)_i$. (perimeter)$_i$ . (length)$_i$ ; Where: $f_s$= skin friction stress along pile

Use lower of the following: $f_s = 0.5\sqrt{(s_u\, \sigma'_{zo})}$ or $f_s = 0.5\, (s_u^{0.75})(\sigma'_{zo})^{0.25}$

$S_u$ = Undrained shear strength (typically use remolded $S_u$ for driven piles).

**(b.2) End bearing**

$f_b = N_c(S_u)_b$

$Q_b = N_c(S_u)_b\, A_b$

Where:
$f_b$ = End bearing capacity (stress)

$(S_u)_b$ = Undrained shear strength at pile tip level

$N_c$ = Bearing capacity coefficient; $N_c = 9$ for $(S_u)_b > 25$ kPa; $N_c = 6$ for $(S_u)_b < 25$ kPa.

$A_b$ = Pile tip (base) cross sectional area

**(c) Pile Capacity in coarse-grained soils**

**(c.1) Shaft Friction**

$Q_f = \Sigma\ \beta_i . (\sigma'_z)_i . (\text{perimeter})_i . (\text{length})_i$

Where:

i given above refers to the i[th] layer of soil; $\delta$ = pile-soil interface friction angle;

$\beta$ = empirical factor → use $\beta = (1-\sin\phi'_{cs})(\tan\delta)$ – Burland (1973)

$\phi'_{cs}$ = critical state friction angle of soil

$\sigma'_z$ = vertical effective stress; $\sigma'_x$ = lateral effective stress

**(c.2) End bearing**

$Q_b = f_b . A_b$

$Q_b = N_q . (\sigma'_z)_b . A_b$

Where

$N_q$ = Bearing capacity coefficient → use $N_q = 0.6^* \exp[0.126\,(\phi'_{cs})_b]$

$(\sigma'_z)_b$ = vertical effective stress at end bearing level

$A_b$ = cross sectional area of pile at pile tip level

$(\phi'_{cs})_b$ = critical state friction angle of soil at pile tip level in degrees

Figure Q.1 (for Question 1)