

THIS EXAMINATION CONSISTS OF 12 PAGES (INCLUDING THIS PAGE).
PLEASE CHECK THAT IT IS COMPLETE.

THE UNIVERSITY OF BRITISH COLUMBIA

Department of Civil Engineering

FINAL EXAMINATION – DECEMBER 2010

SOIL MECHANICS II - CIVL 311

Instructor: Dr. Dharma Wijewickreme

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 = 180
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Marks **Question 1**

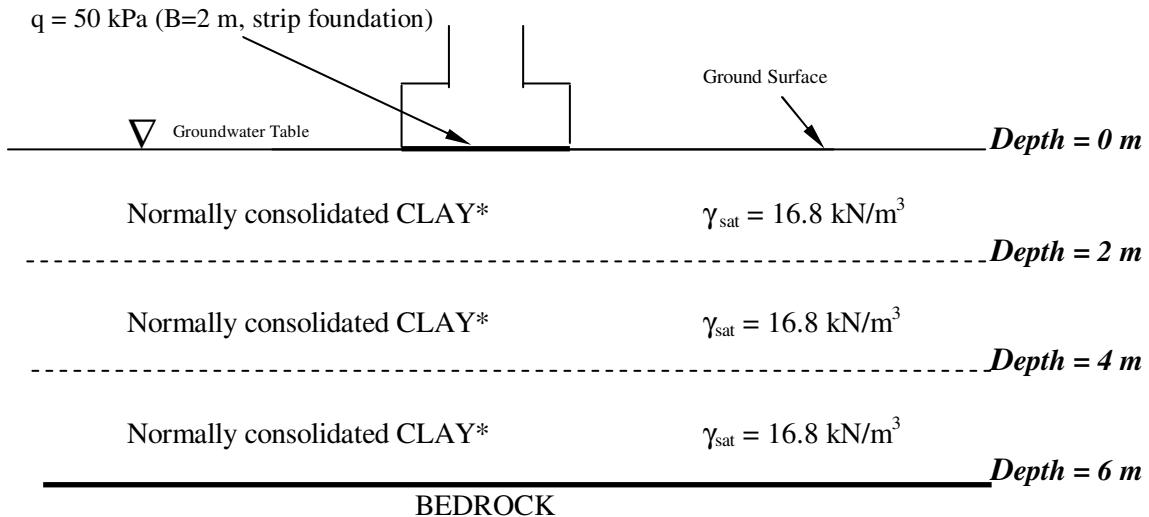
The schematic diagram below illustrates a foundation configuration considered as a part of a preliminary design phase of a building development. As noted, the subject site is underlain by a normally consolidated (NC) clay. The results obtained from laboratory 1-D consolidation testing conducted on undisturbed samples of soil retrieved from the clay deposit led to the following field relationship between void ratio (e) and vertical effective stress (σ_v'):

$$e = 0.70 - 0.15 \log (\sigma_z'/100) \text{ where } \sigma_z' = \text{vertical effective stress in kPa.}$$

It has been suggested that uniform vertical bearing pressure of 50 kPa over the foundation area as shown in the diagram be considered for design purposes. The vertical stress increase $\Delta\sigma_z$ at a depth z vertically beneath the centre line of a strip footing loaded with a uniform pressure q is given by $\Delta\sigma_z = q * I_z$. The values of I_z at several z/B ratios computed using elastic theory are given below:

z/B Ratio	Stress Influence Factor I_z
0.50	0.80
1.50	0.40
2.50	0.25

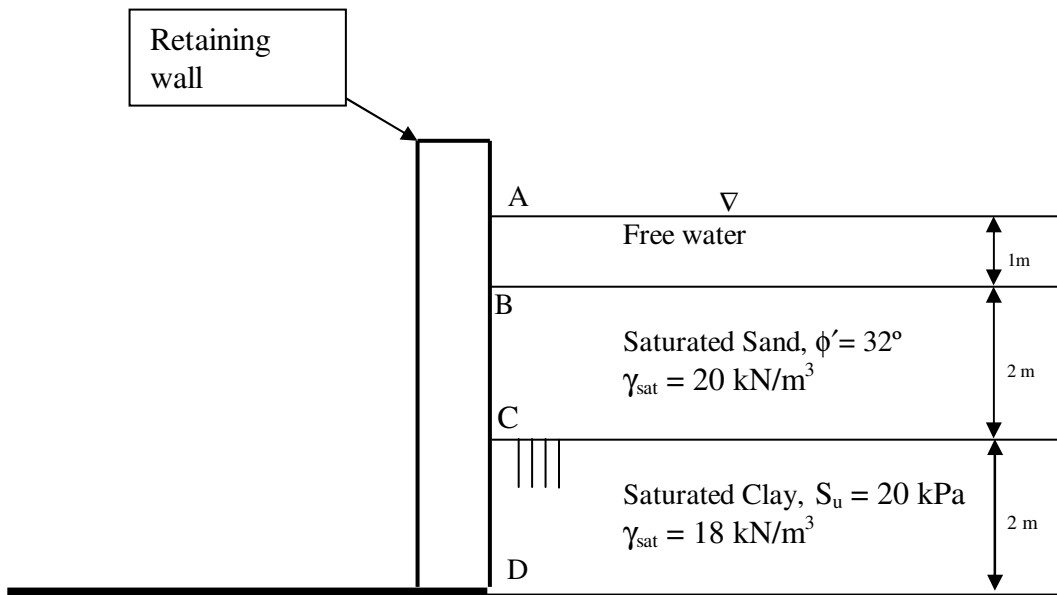
- (30) (a) Estimate the expected:
- (i) distortion settlement; and
 - (ii) ultimate consolidation settlement within the clay deposit
- due to the applied load from the circular foundation [Note: (a) In computing consolidation settlements, divide the stress influence zone of the clay deposit into three sub-layers of equal thickness as shown and assume that the stress conditions at the mid-depth of each sub-layer are representative of that sub-layer; (ii) ignore settlements due to secondary compression; (iii) compute separate initial void ratios (e_o) for each layer in your calculations; (iii) For the NC clay: $E_u = 5$ MPa; Skempton Pore Pressure Coefficient $A_f = 1.0$].
- (10) (b) Estimate the time required for completion of 50% of the total consolidation settlement within the clay deposit due to the placement of the foundation load. Assume that the load is placed is relatively quickly and that the average coefficient of consolidation (C_v) of the clay deposit is 5.0×10^{-4} cm²/sec.



* For your computation purposes, assume that properties γ_{sat} , S_u , E_u , C_c , C_v are constant for the whole deposit of normally consolidated clay.

Question 2

- (40) (a) The design concept for an earth retaining structure is presented in the figure below. As shown, in addition to the soil, the design should account to retain 1 m depth of free water above the saturated sand mass. Using the strength and density parameters as given, 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 ground water conditions, and use Rankine theory for the computations.



NOTE: Not to scale; schematic diagram only.

Question 2 (continued..)

- (20) (b) Using sketches of effective stress Mohr circles and failure envelopes, illustrate your understanding of the active and passive lateral earth pressure conditions considering a dry sand deposit with a horizontal ground surface and an internal effective friction angle of ϕ' .

Question 3

- (25) (a) Given the following information, compute the ultimate bearing capacity of a 3.0 m square footing founded on a sand deposit.
- (i) Peak friction angle: $\phi'_p = 34^\circ$;
 - (ii) Depth of footing base below ground surface = $D_f = 1.0$ m;
 - (iii) Groundwater table is located 0.75 m below base of footing;
 - (iv) Total unit weight of sand above groundwater level = 16.8 kN/m^3
 - (v) Total unit weight of sand below groundwater level $\gamma_{\text{sat}} = 19.8 \text{ kN/m}^3$
- (15) (b) A strip footing, 1 m in width, is to be founded on a clay deposit. The depth of footing embedment (D_f) is 0.75 m, and the soil has a total (saturated) unit weight of 17 kN/m^3 . Laboratory unconsolidated undrained (UU) compression strength testing (i.e., similar to the testing that was performed in your CIVL 311 laboratory class) conducted on undisturbed samples obtained from this clay resulted in a deviator stress at failure of 40 kPa. Determine the ultimate bearing capacity of the foundation.

Question 4

- (20) (a) A closed-ended steel pipe pile (i.e., closed-ended cylindrical steel pile) having a diameter of 0.46 m is driven to a depth of 10 m into homogeneous normally consolidated clay. 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 the clay deposit: S_u (remoulded) = 30 kPa; $\gamma_{\text{sat}} = 16.8 \text{ kN/m}^3$
 - (ii) Groundwater table is located at the ground surface;
 - (iii) Assume that shaft frictional stress (f_s) computed considering vertical effective stress (σ'_{z0}) at mid length of pile can be considered applicable for the full length.
- (20) (b) A timber pile having an average diameter of 0.3 m is driven to a depth of 10 m into saturated sand deposit. Given the following information, estimate the allowable pile load capacity assuming a factor of safety of 2.0. Ignore weight of pile.
- (i) Soil parameters for sand: Critical state friction angle (ϕ'_{cs}) = 30° ; interface friction angle (δ) at the timber-sand interface = 27° ; and $\gamma_{\text{sat}} = 19.8 \text{ kN/m}^3$
 - (ii) Groundwater table is located at the ground surface;
 - (iii) Assume that shaft frictional stress β (σ'_z) computed considering vertical effective stress (σ'_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

$$\sigma'_z = \sum \gamma_i h_i; \quad \sigma' = \sigma - u;$$

γ_i = Bulk unit weight of i th layer of soil;
 h_i = Thickness of i th layer of soil;
 σ'_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)

$$h_{\text{total}} = h_{\text{pwp}} + h_{\text{elev}}$$

$$h_{\text{total}} = (u/\gamma_w) + z_{\text{above-datum}}$$

$$\text{Hydraulic gradient between A and B} = i_{AB} = [(h_{\text{total}})_{\text{at point A}} - (h_{\text{total}})_{\text{at point B}}] / L_{AB}$$

Where L_{AB} = Distance between points A and B

Consolidation Settlements

For a given layer,

Consolidation settlement = $\rho_{pc} = \epsilon_z \cdot H_0$ where

$$\epsilon_z = [\Delta e / (1+e_o)];$$

H_0 = Initial thickness of the layer considered for calculating consolidation settlements;

e_o = initial void ratio;

Δe = change in void ratio;

Based on this, for normally consolidated soil,

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

$$\sigma'_{\text{fin}} = \sigma'_{z_o} + \Delta \sigma'_z$$

σ'_{z_o} = initial vertical effective stress; $\Delta \sigma'_z$ = vertical stress increase

C_c = Compression index; σ'_{fin} = final vertical effective stress

Based on this, for overconsolidated soil,

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

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

C_r = Recompression index;

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

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

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

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 = σ'_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 = σ'_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 = σ_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 = σ_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_γ, s_c - Shape of Footing

d_q, d_γ, d_c - Depth of Footing Embedment

w_q, w_γ - Groundwater level

S_u - Undrained shear strength

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

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

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

Davis and Booker (1971)³:

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

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

Ueno et al. (1998)⁴:

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

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

Effective Footing Dimensions

$$B' = B - 2e_B$$

$$L' = L - 2e_L$$

Definition of the factors to account for the different variations:

s_q, s_γ, s_c - Shape of Footing

d_q, d_γ, d_c - Depth of Footing Embedment

w_q, w_γ - Groundwater level

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

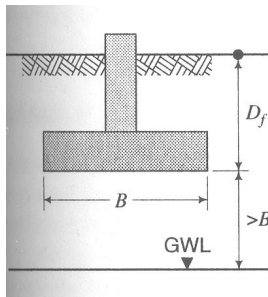
$$d_q = 1 + [2 * \tan \phi'_p] * (1 - \sin \phi'_p)^2 * \tan^{-1}(D_f/B') \text{ for } (D_f/B') > 1$$

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

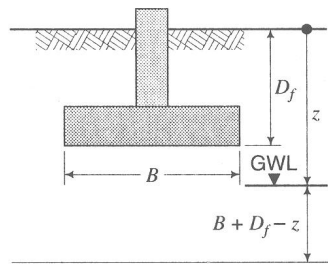
$$d_\gamma = 1$$

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

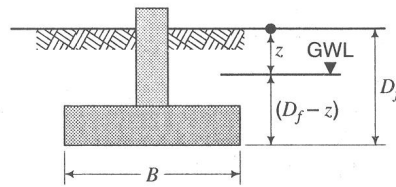
$$d_c = 1 + [0.33 * (D_f/B')] \text{ for } (D_f/B') \leq 1$$



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



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



Case 3: $Z < D_f$

$$\text{Case}_1: w_q = 1; w_\gamma = 1$$

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

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

Estimation of settlements of foundations on clay

(a) Distortion Settlements in clay

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

When

ρ_e = distortion settlement

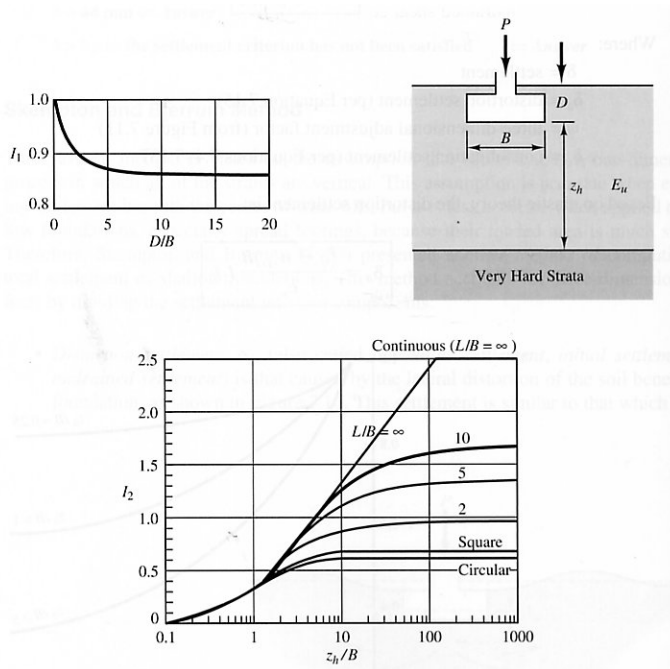
q = bearing pressure

σ'_{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)

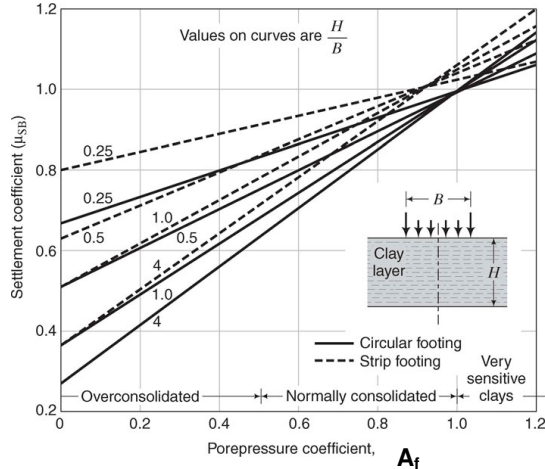
E_u = undrained modulus of elasticity of soil



(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

$$C_a = -\frac{(e_i - e_p)}{\log(t/t_p)}; t > t_p$$

$$\rho_{sc} = \frac{H_0}{(1 + e_p)} C_a \log(t/t_p)$$

Estimation of settlements of foundations on sand

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

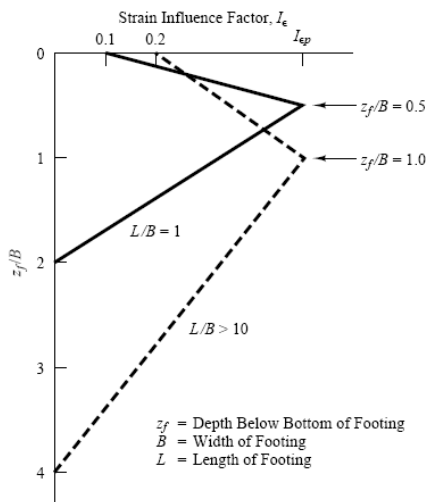
$$C_2 = 1 + 0.2 \log \left(\frac{t}{0.1} \right)$$

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

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

Where:

- ρ = 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
- σ'_{zD} = effective vertical stress at a depth D below the ground surface
- I_ϵ = 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 $I_\epsilon = I_{ep} = 0.5 + 0.1 \sqrt{[(q - \sigma'_{zd}) / \sigma'_{zp}]}$

σ'_{zp} = value of vertical effective stress at I_{ep}

σ'_{zd} = vertical effective stress at foundation level; q = bearing pressure

Load Capacity of Pile foundations

(a) Axial Pile Capacity - Static Pile Analysis

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

$Q_b \gg Q_f$ End Bearing Pile; $Q_f \gg Q_b$ 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

$Q_f = \sum (f_s)_i \cdot (\text{perimeter})_i \cdot (\text{length})_i$; 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

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

Where:

i given above refers to the i^{th} layer of soil; δ = pile-soil interface friction angle;

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

ϕ'_{cs} = critical state friction angle of soil

σ'_z = vertical effective stress; σ'_x = lateral effective stress

(c.2) End bearing

$$Q_b = f_b \cdot A_b$$

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

Where

N_q = Bearing capacity coefficient \rightarrow use $N_q = 0.6 \cdot \exp[0.126 (\phi'_{cs})_b]$

$(\sigma'_z)_b$ = 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