APPENDIX F

CORRELATION EQUATIONS

F – 1 In-Situ Tests

1. SPT

(1) Sand

\[ N_{60} = \frac{(\phi' - 20)^2}{15.4} \times \left(\frac{\sigma'_{vo}}{P_a}\right)^{0.5} \]  
(Hatanaka and Uchida, 1996)

where,

- \(\sigma'_{vo}\) = effective vertical stress
- \(\phi'\) = effective friction angle
- \(P_a\) = atmosphere pressure

\[ N_{60} = (\tan \phi')^{1/0.34} \cdot (12.2 + 20.3 \cdot \sigma'_{vo}/P_a) \]  
(Shmertmann, 1975)

(2) Clay and Silt

\[ N_{60} = \frac{1}{0.47 \times P_a} \times \left[ \left(\frac{2 \times S_u}{\sigma'_{vo} \times \sin \phi'}\right)^{1/0.8} \times \sigma'_{vo} \right] \]  
(Mayne and Kemper, 1988)

where,

- \(S_u\) = undrained shear strength

2. CPT

(1) Sand

1) Cone resistance

\[ q_c = \sigma'_{vo} \times 10^{\left[\frac{\left(\tan \phi'-0.1\right)}{0.38}\right]} \]  
(Robertson and Campanella, 1983)

\[ q_c = (\sigma'_{vo} \cdot P_a)^{0.5} \times 10^{\left[\frac{\left(\phi'-17.6\right)}{11.0}\right]} \]  
(Kulhawy and Mayne, 1990)

2) Sleeve friction

\[ f_s = \sigma'_{vo} \times \left(\tan (45 + \frac{\phi'}{2})\right)^2 \times \tan \left(\frac{\phi'}{3}\right) \]  
(Masood and Mitchell, 1993)

(2) Clay and Silt

1) Cone resistance

\[ q_c = \sigma_{vo} + 3 \times \left[\left(\frac{2 \times S_u}{\sigma_{vo} \times \sin \phi'}\right)^{1/0.8} \times \sigma'_{vo}\right] \]  
(Mayne, 1995)

where,

- \(\sigma_{vo}\) = total vertical stress
2) Sleeve friction
\[ f_s = \sigma_v' \times \left(\tan \left(45 + \frac{\phi'}{2}\right)\right)^2 \times \tan \left(\frac{\phi'}{3}\right) \] (Masood and Mitchell, 1993)

3) Pore pressure
\[ u_2 = \frac{1}{0.53} \times \left(\frac{2 \times S_u}{\sigma_v' \times \sin \phi'}\right)^{1/0.8} \times \sigma_v' + u_0 \] (Larsson and Mulabdic, 1991)

where
\[ u_0 = \text{steady state pore water pressure} \]

3. DMT

(1) Sand
1) Lift-off pressure, \( P_0 \)
\[ P_0 = K_D \times \sigma_v' + u_0 \] (Garcia, 1991)

\[ K_D = \left(\frac{\phi'}{37.3}\right)^{1/0.082} \times (K_0 + 0.8) + 0.8 \] (Campanella and Robertson, 1991)

where,
\[ K_0 = \text{the coefficient of earth pressure at rest} \]

2) Expansion pressure, \( P_1 \)
\[ P_1 = 25.99 \times (P_0)^{0.68} \] (Garcia, 1991)

(2) Clay
1) Lift-off pressure, \( P_0 \)
\[ P_0 = \sigma_p'_{0.51} + u_0 \] (Mayne, 1995)

where
\[ \sigma_p' = \text{effective preconsolidation stress} \]

2) Expansion pressure, \( P_1 \)
\[ P_1 = 1.6 \times (P_0)^{0.98} \] (Garcia, 1991)

(3) Silt
1) Lift-off pressure, \( P_0 \)
\[ P_0 = \sigma_p'_{0.51} + u_0 \] (Mayne, 1995)
2) Expansion pressure, P1

\[ P_1 = 1.7 \times (P_0)^{1.02} \] (Garcia, 1991)
F – 2 Laboratory Tests

1. Total Unit Weight
\[ \gamma_t = \left( \frac{G_s + S \cdot e}{1 + e} \right) \cdot \gamma_w \]
where
- \( G_s \) = specific gravity
- \( S \) = saturation
- \( e \) = void ratio
- \( \gamma_w \) = unit weight of water

2. Modified Compaction Test

(1) Maximum Dry Unit Weight

1) Sand
\[ \gamma_{d \, \text{max}} = \frac{G_s}{1 + e_{\text{min}}} \cdot \gamma_w \]
\[ e_{\text{min}} = \left( \frac{D_r}{100} - 1 \right) \cdot (0.23 + 0.06/D_{50}) + e \]
(Shimobe and Moroto, 1995)
where
- \( D_r \) = relative density
- \( D_{50} \) = diameter corresponding to 50% finer (mm)
\[ D_r = -240.96 \cdot e + 194.98 \]
(Das, 1997)
\[ w_{\text{opt}} = \frac{0.95 \times G_s}{\gamma_{d \, \text{max}}} \cdot \gamma_w - 1 \]

2) Clay and Silt
\[ \gamma_{d \, \text{max}} = (2.27 \cdot \log_{10} LL - 0.94) \cdot \log_{10} 2693.3 - 0.16 \cdot LL + 17.02 \]
(Blotz et., 1998)
where
- \( LL \) = liquid limit
\[ w_{\text{opt}} = (12.39 - 12.21 \cdot \log_{10} LL) \cdot \log_{10} 2693.3 + 0.67 \cdot LL + 9.21 \]
(Blotz et., 1998)

3. Water Content
\[ w = \frac{S \cdot e}{G_s} \]
4. 1-D Consolidation Test

(1) Compression Index, $C_c$

1) Sand

$$C_c = 0.75 \times (e - 0.5)$$ (Azzouz et al., 1976)

2) Clay

$$C_c = 0.009 \times (\text{LL} - 10)$$ (Terzaghi and Peck, 1967)

$$C_c = 1.15 \times (e - 0.35)$$ (Azzouz et al., 1976)

$$C_c = 0.141 \cdot G_s^{1.2} \cdot \left(1 + \frac{e}{e_o}\right)^{2.38}$$ (Rendon-Herrero, 1983)

$$C_c = 0.2343 \times \text{LL} \times G_s$$ (Nagaraj and Murty, 1985)

3) Silt

$$C_c = 0.3 \times (e - 0.27)$$ (Azzouz et al., 1976)

(2) Recompression Index, $C_r$

$$C_r = 0.15 \times C_c$$ (Holtz and Kovacs, 1981)

$$C_r = 0.0463 \times \text{LL} \times G_s$$ (Nagaraj and Murty, 1985)

(3) Coefficient of Consolidation, $C_v$

$$C_v = 116.45 \cdot \text{LL}^{-2.8784}$$ (US Navy, 1971)

(4) Permeability, $k$

1) Sand

$$k = c \cdot (D_{10})^2$$ (Hazen, 1911)

where

- $k$ = permeability ($\text{cm/s}$)
- $c = 0.4 \sim 1.2$ with average value of 1
- $D_{10} = \text{diameter corresponding to 10% finer (mm)}$

$$k = 1.5046 \cdot \left[\frac{50 - D_{10} - 10 - D_{50}}{40} + 0.025 \cdot (D_{50} - D_{10})\right]^2$$ (Alyamani and Sen, 1993)

$$k = \frac{(D_{50})^2 \cdot n^3 \cdot \rho g}{180 \cdot (1 - n)^2 \cdot \mu}$$ (Carman, 1956)

where

- $n = \text{porosity}$
- $g = \text{acceleration of gravity (980 cm/s}^2\text{)}$
- $\rho = \text{water density (0.9982 g/cm}^3\text{ at 20°C)}$
- $\mu = \text{dynamic viscosity of water (0.01 g/cm} \cdot \text{s at 20°C)}$
2) Clay

\[ k = 1.5046 \cdot \left[ \frac{S_{10} - S_{10} - D_{50}}{40} + 0.025 \cdot (D_{50} - D_{10}) \right]^2 \] (Alyamani and Sen, 1993)

\[ k = \frac{(D_{50})^2 \cdot n^2 \cdot p \cdot g}{180 \cdot (1-n)^2 \cdot \mu} \] (Carman, 1956)

(5) Coefficient of Compressibility, \(a_v\)

\[ a_v = \frac{k(1+e)}{C_v \gamma_w} \]

(6) Coefficient of Volume Compressibility, \(m_v\)

\[ m_v = \frac{a_v}{1+e} \]

5. Triaxial Test

(1) Undrained Shear Strength, \(S_u\)

1) Sand

\(S_u = \text{not applicable}\)

2) Clay and Silt

\[ S_u = \sigma'_p \times (-0.00002314 \cdot \text{PI}^2 + 0.00462032 \cdot \text{PI} + 0.11522951) \] (Mesri, 1975)

where

\(\text{PI} = \text{plasticity index}\)

(2) Effective Friction Angle, \(\phi'\)

1) Sand

\[ \phi' = 33 + 3 \cdot I_R \] (Bolton, 1986)

\[ I_R = D_t \cdot (10 - \ln \pi') - 1 \]

\[ D_t = -240.96 \cdot e + 194.98 \] (Das, 1997)

where

\(I_R = \text{relative dilatancy index}\)

\(\pi' = \text{mean effective stress at failure}\)

2) Clay and Silt

\[ \phi' = 0.00147 \cdot \text{PI}^2 - 0.2811 \cdot \text{PI} + 35.90646 \] (Bjerrum and Simons, 1960)
6. Resonant Column Test

(1) Small-strain shear modulus, \( G_{max} \)

\[
G_{max} = \frac{625 \cdot (OCR)^{k_1} \cdot P_a^{0.5} \cdot \sigma_0^{0.5}}{0.3 + 0.7 \cdot e^2} \quad \text{(Hardin, 1978)}
\]

where

\( k_1 = -4 \cdot 10^{-5} \cdot (P_I)^2 + 0.0095 \cdot (P_I) + 0.0014 \)

\( \sigma_0 = \) effective mean principal stress
A given site is to receive a multi-story structure, whose conditions are defined as:

**Building Type:** Three-story rectangular building  
**Structure Condition:** Light-steel concrete building  
**Building Dimension:** 60 m x 60 m  
**Budget Condition:** Limited

After carefully reading the following “introduction to site investigation”, calculate a proper total boring number and a proper boring/sounding depth on the basis of methods suggested by U.S. Army Corps of Engineers (2001) and Sowers and Sowers (1970) mentioned in the following introduction, respectively. Based on the following “instruction for site investigation simulation program”, perform a site investigation at a given site to explore the subsurface conditions of the proposed structure executing appropriate in-situ tests and laboratory tests within a given budget. Determine the number of soil layer, soil type of each soil layer, thickness of each soil layer, ground water table, and such soil parameters in each soil layer as total unit weight, effective friction angle, hydraulic conductivity, and shear wave velocity, etc. Make sure that you should save your performance assessment as a text file, print the file. Please, SUBMIT it and quiz with your GT ID # and name right before leaving here.

**Introduction to Site Investigation**

Site investigation is an activity to explore the subsurface conditions which underlie a proposed structure. It is to obtain information to get geotechnical engineers to recommend an economical final grading via identifying unsuitable soil conditions at a given site, evaluate the allowable bearing capacity and dimension of foundation of the proposed structure, make a recommendation for cut or fill slopes, aid seismic design of
the proposed structure and provide efficient construction methods on the basis of information of ground water and intact rock. In-situ tests such as standard penetration test (SPT), cone penetration test (CPT), and dilatometer test (DMT) and laboratory tests such as Atterberg limits, sieve analysis, specific gravity, hydraulic conductivity, one-dimensional consolidation test, compaction test, triaxial test, and resonant column test should be performed to obtain the above information.

Prior to performing a site investigation, the proper number of boring/sounding and proper boring/sounding depth for the proposed structure should be determined. U.S. Army Corps of Engineers (2001) suggested one boring per 230 square meters of ground floor for rigid frame structures. It is very important that at least one boring at each corner of the proposed structure plan should be performed. Sowers and Sowers (1970) showed approximate correlations of the minimum boring/sounding depth with story number for rigid frame structures as follows:

- For light steel or narrow concrete buildings

\[ D_b = 3 \cdot S^{0.7} \]

where

- \( D_b \): depth of boring (meter)
- \( S \): number of stories

- For heavy steel or wide concrete buildings

\[ D_b = 6 \cdot S^{0.7} \]

As the next step, in-situ tests should be performed within a given budget. SPT provides N values (blow counts per foot) as indicator of soil strength. The following table presents the general correlation of N value with soil type and consistency. Soil types can be approximately estimated using the table.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>N value (blow count/ft)</th>
<th>Consistency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0-4</td>
<td>Very loose</td>
</tr>
<tr>
<td></td>
<td>5-10</td>
<td>Loose</td>
</tr>
<tr>
<td></td>
<td>11-30</td>
<td>Firm</td>
</tr>
<tr>
<td></td>
<td>31-50</td>
<td>Dense</td>
</tr>
<tr>
<td>Silt and clay</td>
<td>Over 50</td>
<td>Very dense</td>
</tr>
<tr>
<td>--------------</td>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td></td>
<td>0-2</td>
<td>Very soft</td>
</tr>
<tr>
<td></td>
<td>3-4</td>
<td>Soft</td>
</tr>
<tr>
<td></td>
<td>5-8</td>
<td>Firm</td>
</tr>
<tr>
<td></td>
<td>9-15</td>
<td>Stiff</td>
</tr>
<tr>
<td></td>
<td>16-30</td>
<td>Very stiff</td>
</tr>
<tr>
<td></td>
<td>31-50</td>
<td>Hard</td>
</tr>
<tr>
<td></td>
<td>Over 50</td>
<td>Very hard</td>
</tr>
</tbody>
</table>

Cone resistance as resistance to cone penetration, sleeve friction as frictional resistance of soil surrounding the cone, and pore water pressure can be obtained from CPT. Ground water table beneath surface is usually identified from the pore water pressure of CPT. It is known that most clay and silt soil layers have cone resistance of less than 18,000 kPa. Without ground water, the pore water pressure of CPT is zero. Furthermore, lift-off pressure and expansion pressure are estimated from DMT. These pressures are used to determine soil indices such as material index and horizontal stress index and soil stiffness such as dilatometer modulus, thereby classifying soil type.

Soil layer thickness and soil type within the depth, which satisfies the minimum boring/sounding depth obtained via the correlations of Sowers and Sowers (1970) introduced above, can be approximately classified by the soil parameters obtained from the above in-situ tests. However, in order to perform more accurate estimation of soil classification, the results of laboratory tests implemented within a given budget using undisturbed in-place soil samples should be compared with those of the in-situ tests. The next step is to perform laboratory tests with undisturbed in-place soil samples. The undisturbed in-place soil samples can be obtained from one of boring methods including solid flight auger, hollow stem auger, rotary wash boring, and percussive drilling. The following table shows the soil parameters obtained from main laboratory tests.
<table>
<thead>
<tr>
<th>Test type</th>
<th>Soil parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM D4318 – Atterberg limits test</td>
<td>Plastic limit and liquid limit</td>
</tr>
<tr>
<td>ASTM D1557 – Modified compaction test</td>
<td>Maximum dry unit and optimum water content</td>
</tr>
<tr>
<td>ASTM D2435 – One-dimensional consolidation test</td>
<td>Compression index and coefficient of consolidation</td>
</tr>
<tr>
<td>ASTM D5084 – Hydraulic conductivity test</td>
<td>Hydraulic conductivity</td>
</tr>
<tr>
<td>ASTM D4015 – Resonant column test</td>
<td>Shear wave velocity and damping ratio</td>
</tr>
<tr>
<td>ASTM D4767 - Consolidated and undrained triaxial test</td>
<td>Undrained shear strength and effective friction angle</td>
</tr>
</tbody>
</table>

As an example, soil type can be easily identified based on the result of hydraulic conductivity: hydraulic conductivity of clay is less than $10^{-7}$ cm/sec and hydraulic conductivity of silt ranges from $10^{-4}$ cm/sec to $10^{-6}$ cm/sec; sand has hydraulic conductivity greater than $10^{-3}$ cm/sec. The obtained hydraulic conductivity can be used to design landfill barriers. In addition, undrained shear strength and effective friction angle obtained from consolidated and undrained triaxial test is used to estimate soil strength, thereby estimating an allowable bearing capacity of a foundation.
APPENDIX H
APPENDIX H

QUIZ

Please, answer the following questions and submit it with your GT ID # and name before leaving here.

(Questions 1 – 6)
General in-situ tests are given in the following table.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>SPT (standard penetration test)</td>
</tr>
<tr>
<td>2.</td>
<td>CPT (cone penetration test)</td>
</tr>
<tr>
<td>3.</td>
<td>DMT (Dilatometer test)</td>
</tr>
</tbody>
</table>

Choose one of the test types above which the following individual soil property is obtained from:

1. N value
2. Cone resistance
3. Sleeve friction
4. Pore pressure
5. Lift-off pressure
6. Expansion pressure
General laboratory tests are given in the following table.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ASTM D421&amp;D422 – Sieve analysis and hydrometer</td>
<td>6. ASTM D4015 – Resonant column test</td>
</tr>
<tr>
<td>2. ASTM D854 – Specific gravity</td>
<td>7. ASTM D4318 – Atterberg limits</td>
</tr>
<tr>
<td>3. ASTM D1557 – Modified compaction test</td>
<td>8. ASTM D4767 – Triaxial test (CU)</td>
</tr>
<tr>
<td>5. ASTM D2435 – 1-D consolidation test</td>
<td></td>
</tr>
</tbody>
</table>

Choose one of the test types above which the following individual soil parameter is obtained from:

7. Maximum dry density
8. Optimum moisture content
9. Coefficient of consolidation
10. Compression index
11. Plastic limit
12. Permeability
13. Shear wave velocity
14. Undrained shear strength
15. Effective friction angle
16. U.S. Army Corps of Engineers (2001) suggested at least one boring per 230 square meters of ground floor for rigid frame structures. Specify boring locations necessary to perform site investigation on grid intersections of a given concrete building area?

![Grid Intersection Diagram]

17. Sowers and Sowers (1970) showed approximate correlations of the minimum sampling depth with story number for rigid frame structures as follows:

- For light steel or narrow concrete buildings
  \[ D_b = 3 \cdot S^{0.7} \]

- For heavy steel or wide concrete buildings
  \[ D_b = 6 \cdot S^{0.7} \]

where

- \( D_b \): depth of boring (meter)
- \( S \): number of stories

Calculate the minimum boring depth for a four-story building with 40 m × 40 m light-steel building dimension.

18. What is the minimum length of sampling interval for SPT?

19. What is the minimum length of sampling interval for boring?

20. What is the soil property of CPT directly related to water table?
21. Estimate groundwater table using the soil properties in the Figure shown below.

22. Calculate hydrostatic water pressure (kN/m$^2$) at 10.0 m using the soil properties in the Figure shown below (unit weight of water = 9.8 kN/m$^3$).

23. What is generally the value of plastic limit of sand?

24. What is generally the soil type to have the largest value of liquid limit?

25. What soil type(s) is generally effective friction angle obtained for?

26. What soil type(s) is generally undrained shear strength obtained for?
APPENDIX I
APPENDIX I

SITE INVESTIGATION PROGRAM SURVEY FORM

Please answer the following questions related to the site investigation program:

1. Are the instructions for using the program clear?
   1) Strongly Agree  2) Agree  3) Disagree  4) Strongly Disagree

2. Are you able to use the program independently?
   1) Strongly Agree  2) Agree  3) Disagree  4) Strongly Disagree

3. Are the Help Messages provided by the software readily understandable?
   1) Strongly Agree  2) Agree  3) Disagree  4) Strongly Disagree

4. Is the graphical user interface well organized?
   1) Strongly Agree  2) Agree  3) Disagree  4) Strongly Disagree

5. Does the program help you understand the objectives of a site investigation program?
   1) Strongly Agree  2) Agree  3) Disagree  4) Strongly Disagree

6. Does the program help you to see the overall scope of a site investigation?
   1) Strongly Agree  2) Agree  3) Disagree  4) Strongly Disagree

7. Does the program help you to perform a simulated site investigation in a logical way?
   1) Strongly Agree  2) Agree  3) Disagree  4) Strongly Disagree

8. Do you think the program will be helpful for undergraduate students enrolled in an introductory geotechnical engineering course?
   1) Strongly Agree  2) Agree  3) Disagree  4) Strongly Disagree

9. How would you rate the overall quality of the software?
   1) Excellent  2) Good  3) Fair  4) Poor

10. Please provide any additional comments and suggestions you like.