CEE 6443

Class Notes

FOUNDATION SYSTEMS

Applied Geotechnical Analysis and Evaluation

by

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TOPICS

- **Geotechnical Site Characterization**
- **Geostatic Stress State**
  (Overburden, Preconsolidation, e_o, OCR, K_o)
- **Bearing Capacity**
  (Static Equilibrium, Limit Plasticity, Cavity Expansion)
- **Shallow Foundations**
  - **Spread Footings**
  - **Structural Mats/Rafts**
  - **Deformations (deflections, displacements, settlements.**
  - **Dynamically-loaded footings**
- **Ground Modification**
- **Deep Foundations**
  - **Driven Piles**
  - **Drilled Shafts**
  - **Axial Capacity**
  - **Load Test Interpretation**
  - **Axial Load Transfer**
  - **Displacement Calculations**
- **Lateral & Moment Response of Piles**
  - **Capacity**
  - **Deflections**
- **Nonlinear Load-Displacement-Capacity Response**

CEE-6443 - Foundation Systems

Course Overview: Foundation systems are required for support of buildings, bridges, towers, retaining walls, oil platforms, and other civil engineering structures that reside in and on geomaterials. Notably, all of the structural loads must be somehow transmitted to *Mother Nature*, thus requiring site-specific testing and evaluation of each particular situation. Course reviews analytical procedures for the evaluation of shallow foundation systems (spread footings, structural mats/rafts) and deep foundations (driven piles, augered and bored piles, drilled shafts). Methods reviewed for determination of ultimate bearing capacity and load-displacement behavior, with due consideration of the effects of relative foundation rigidity and angular distortion. The load-displacement response is expressed in the framework of an elastic continuum whereby soil stiffness is represented by an equivalent modulus (E_s) and Poisson's ratio($<_s$). For deep foundation systems, procedures are reviewed for determining the relative components of side and base resistance under axial compression loading using total stress analysis (undrained, or " method), effective stress approach (ß method), and offshore pile analysis (8 method). Additional topics include load transfer distributions, full-scale load testing, installation effects, pile group interaction effects, pile dynamics, as well lateral, moment, uplift, and torsion loading. Beneficial uses of in-situ testing (cone penetration, flat dilatometer, shear wave methods) are discussed in relation to evaluating and forecasting foundation performance.

Instructor: Paul W. Mayne, PhD, P.E., Room 241 Mason (Email: pmayne@ce.gatech.edu)
Course Format: 2 lectures per week; Tuesday-Thursday 09:30-10:55; 3 credits (3-0-3).
Homework Problems: approximately 6 to 8 homeworks/term.
Midterms/Exams: 2 midterms plus final exam.

General Course Topics:

- Geotechnical Site Investigations
    - Natural Geomaterials include soils and rocks; Artificial Fills and Man-Made Deposits
    - Laboratory Evaluation of Soil Engineering Parameters
    - In-Situ Field Testing

- Shallow Foundation Systems
    - Stress Distribution with Depth Beneath Surface Loading
    - Elasticity Solutions for Shallow Foundation Settlement
    - Strain Influence Factors
    - Relative Foundation Rigidity
    - Soil Modulus Characterization and Determination
    - Ultimate Bearing Capacity
    - Limit Equilibrium
    - Upper and Lower Bound Limit Plasticity
    - Cavity Expansion Solutions

- Driven and Bored Pile Foundation Systems
    - Axial Load Transfer
    - Side and Base Resistance Components
    - Pile Dynamics (CAPWAP, PDA, Integrity Testing)
    - Load-Displacement Response of Deep Foundations
    - Axially-Loaded Pile Groups and Interaction Effects
    - Procedures and Interpretation of Pile Load Tests
    - Lateral and Moment Capacity of Piles and Piers
    - Lateral Load-Displacement Behavior of Deep Foundations
    - Pile Groups Under Lateral and Moment Loading
    - Load Resistance Factor Design (LRFD).

Required Readings:
- **CEE 6443 Class Notes**
- **Selected Readings from Manuals, Journals, & Proceedings.**

ABBREVIATIONS FOR REFERENCE MATERIALS

ADSC = Association of Drilled Shaft Contractors (Intl. Assoc. of Foundation Drilling)
API = American Petroleum Institute
ASCE = American Society for Civil Engineers
ASTM = American Society for Testing & Materials
BRE = Building Research Establishment
CGJ = Canadian Geotechnical Journal
DFI = Deep Foundations Institute
EPRI = Electric Power Research Institute
FHWA = Federal Highway Administration
Geot. = Geotechnique (Thomas Telford; British Geotechnical Society).
ISSMGE = Intl. Society for Soil Mechanics & Geotechnical Engineering (www.issmge.org)
ICE = Institution of Civil Engineers (UK).
JGE = Journal of Geotechnical Engineering (ASCE)
JGGE = Journal of Geotechnical & Geoenvironmental Engineering (ASCE)
JSMFD = (old ASCE) Journal of Soil Mechanics & Foundations Division
NGI = Norwegian Geotechnical Institute (www.ngi.no)
NHI = National Highway Institute
NRCC = National Research Council of Canada
NSF = National Science Foundation
NTNH = Norwegian University of Science & Technology, formerly NTH (Norwegian Inst. Tech).
OTC = Offshore Technology Conference
S&F = Soils & Foundations (Japanese Geotechnical Society)
SGI = Swedish Geotechnical Society
WES = Waterways Experiment Station (US Army Corps of Engineers).

Special Proceedings:

BAP = Bored and Augered Piles (Ghent)
ICSMFE = International Conference on Soil Mechanics & Foundation Engineering
ECSMFE = European Conf. On Soil Mechanics & Foundation Engineering
GSP = Geotechnical Special Publication (ASCE Geo-Institute)
NCHRP = National Cooperative Highway Research Publication
STP = Special Technical Publication (ASTM)
TRR = Transportation Research Record

WEBSITES:

Listing of many different pile types and methods of installation:

www.geoforum.com

U.S. University Council on Geotechnical Engineering Research:

www.usucger.org

Federal Highway Administration Research:

http://www.fhwa.dot.gov/bridge/geo.htm

SI CONVERSION FACTORS

Conversions between SI, metric, and Imperial (English) units

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
in	inches	25.4	millimeters	mm
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
ha	hectare (100 m by 100 m)	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
ml	millimeters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
		TEMPERATURE		
°C	Celsius	1.8 C + 32	Fahrenheit	°F
		UNIT WEIGHT and DENSITY		
g/cc	grams per cubic centimeter	62.4	poundforce /cubic foot	pcf
g/cc	grams per cubic centimeter	9.8	kilonewtons per cubic meter	kN/m^3
kN/m^3	kilonewton /cubic meter	6.36	poundforce /cubic foot	pcf
		FORCE and LOAD		
N	newtons	0.225	poundforce	lbf
kN	kilonewtons	225	poundforce	lbf
kg	kilogram (force)	2.205	poundforce	lbf
MN	meganewtons	112.4	tons (force)	t
k	kip (1000 lbf)	2	ton	t
k	kip	4.45	kilonewton	kN
		PRESSURE and STRESS*		
kPa*	kilopascals	0.145	poundforce /square inch	psi
kPa	kilopascals	20.9	poundforce /square foot	psf
MPa	megapascal	10.44	tons per square foot	tsf
kg/cm^2	kilograms per square cm	1.024	tons per square foot	tsf
tsf	tons per square foot	95.75	kiloPascals	kPa

*Notes: 1 kPa = kN/m^2 = one kiloPascal = one kilonewton per square meter.
For dimensionless graphs and equations, a reference stress/pressure of one atmosphere can be used, such that $\sigma_{atm} = p_{atm} = 1$ bar = 100 kPa . 1 tsf . 1 kg/cm^2.

Terminology and Nomenclature for Foundations Systems

" = adhesion factor for pile side friction under undrained loading (i.e., $f_s = c_a =$ " s_u).

ß = effective stress factor for unit side resistance (i.e., f_s = ß F_{vo}').

$ß_{LT}$ = percentage of load transferred to pile base/tip.

$ß_G$ = $E_0/(k_E\ d)$ = normalized Gibson-type soil parameter for modulus rate with depth

) = incremental change in value.

* = foundation deflection

$*_m$ = interface friction angle between soil and foundation material.

$*_h$ = lateral foundation displacement at groundline.

2 = rotation (at ground surface) of pile top (lateral and moment loading).

, = normal strain (e_a = axial strain, e_{vol} = volumetric strain).

$(_T$ = total unit weight of soil. Note that $(_{DRY}$ # $(_T$ # $(_{SAT}$

$(_s$ = shear strain.

8 = side resistance factor for offshore pile approach.

7 = plastic volumetric strain ratio (critical state soil mechanics parameter) . 1 - C_s/C_c.

< = Poisson's ratio is ratio of lateral to vertical strain = -$,_h$/ $,_v$ (sometimes designated :).

N' = effective stress friction angle of soil: normal ranges for clays: 20° # N' # 40°; while general range for sands: 30° # N' # 55°.

F_1 = major principal stress

F_2 = intermediate principal stress

F_3 = minor principal stress, such that: F_1 \$ F_2 \$ F_3.

σ_{atm} = reference stress = 1 atmosphere = 1 bar . 1 tsf . 1 kg/cm^2 . 100 kPa. Also, p_a.

F_{vo}' = (current) effective vertical stress.

F_{ho}' = (current) effective horizontal (or lateral) stress.

F_p' = effective preconsolidation stress, or yield stress in e-log F_v' graph (also, F_{vmax}' or P_c').

F_o' = effective octahedral stress = ⅓ (F_1'+F_2'+F_3').

)F_z = =)F_v = change in vertical stress (similar for)F_x and)F_y).

)F_r = =)F_h = change in radial/horizontal stress (axisymmetric problems).

)F_2 = change in tangential stress (cylindrical coordinate system).

Δu = excess porewater pressure ($u - u_0$).

D = vertical foundation displacement or deflection or settlement (also given by w_t).

D_T = total soil mass density = (/g where (= unit weight and g = 9.8 m/s^2 = grav. constant.

J = shear stress. In triaxial compression, often taken to be J = ½(F_1-F_3).

J_{max} = shear strength or maximum shear stress J (generally, either drained or undrained).

J_s = unit side stress or shaft friction for piles.

. = modifier coefficients for bearing factors to account for shape, depth, inclination, ...

a = (equivalent) foundation radius of circular foundation = ½d

A = footing breadth (long dimension in plan view); sometimes designated as a, l, or L.

A_f = base area of footing or foundation (= A_b for deep foundation).

A_s = surface area of shaft side (A_s = BdL for circular shaft).

A_b = base area of shaft foundation (A_b = Bd^2/4 for circular base).

B = foundation width (short dimension in plan view); also pile diameter sometimes given as b, but also designated d = diameter.

c_a = adhesion or undrained unit side resistance.

c' = effective cohesion intercept; intercept on y-axis of Mohr-Coulomb failure envelope.

c_u = undrained shear strength (also $c_u = s_u$). Note: In old textbooks, it is noted as c = "cohesion" and now archaic. Should not confuse with the parameter c'.

C_M = side resistance modifier for pile foundation material type.

C_K = side resistance modifier for pile installation effects.

C = modifier terms to correct for load transfer to pile base (C_b, C_k, C_n)

Terminology/Nomenclature (continued)

C_c	=	virgin compression index from consolidation graph of e-logσ_v'
C_s	=	swelling (or rebound) index from consolidation graph of e-logσ_v'
C_r	=	recompression index from consolidation graph of e-logσ_v'
d	=	foundation diameter (also designated B in some references) or equivalent diameter of a circular foundation.
D	=	depth of foundation (also given as L for length).
D'	=	constrained modulus from one-dimensional compression (D' = $\Delta\sigma_v'/\Delta\varepsilon_v$)
E	=	elastic or Young's modulus.
E'	=	drained elastic modulus;
E_u	=	undrained elastic modulus.
E_f	=	modulus of foundation element (material).
E_p	=	modulus of pile or deep foundation.
E_s	=	equivalent elastic soil modulus (Young's modulus), where E = 2G(1+<).
F_c, F_q	=	bearing factors from cavity expansion theory
e	=	eccentricity of load (height of lateral load above groundline).
f_s	=	unit side resistance or unit skin friction (general term for undrained or drained).
f_s	=	measured cone sleeve friction
G	=	shear modulus (secant value: G = J/( ).
G_{max}	=	maximum shear modulus, or initial tangent shear modulus = $\rho_T V_s^2$
G_0	=	maximum shear modulus, or initial tangent shear modulus (G_{max})
h	=	depth to incompressible rigid layer (i.e., unweathered rock); also designated H.
H	=	lateral load or force.
H_u	=	ultimate lateral load or lateral capacity.
H	=	depth to bedrock
i	=	stress influence factor (ratio stress at depth to unit surface stress); also designated as J.
I	=	displacement influence factor for shallow foundation from elastic continuum theory.
I_0	=	influence factor for rigid pile in undrained
I_G	=	influence factor for Gibson-type soil; I_H (homogeneous modulus); I_F (flexibility), I_E (embedment)
I_ρ	=	displacement influence factor for pile foundation in semi-infinite medium.
I_ρ	=	general displacement influence factor for axial pile foundation
I_R	=	G/τ_{max} = rigidity index of the soil. For undrained loading, $I_R = G/s_u$
K_f	=	foundation flexibility or stiffness factor (relative to soil stiffness).
K	=	ratio of effective lateral stress to effective vertical stress (general).
K_i	=	(initial) stiffness of foundation = load/deflection.
K_o	=	$\sigma_{ho}'/\sigma_{vo}'$ = lateral stress ratio (geostatic state implies zero lateral strain).
K_P	=	passive earth pressure coefficient; For Rankine case, K_p = (1+sinN')/(1-sinN').
K_A	=	active earth pressure coefficient; For Rankine case, K_A = (1-sinN')/(1+sinN').
k	=	coefficient of permeability (hydraulic conductivity of the soil).
k_s	=	subgrade reaction parameter = q/* = applied surface stress divided by deflection.
k_z	=	vertical spring constant = Q/* = applied surface force divided by deflection
k_E	=	rate of increase of soil modulus with depth (Gibson soil) =)E_s/)z.
L	=	foundation length (also designated D for depth); sometimes L = plan breadth.
M	=	moment (for lateral loading, M = H@e, where e = eccentricity).
M'	=	constrained modulus; M' = D' =)F_v/) ,$_v$ from 1-d compression test (consolidation test).
M_c	=	6 sin ϕ'/(3 - sin ϕ') = friction parameter of soil in critical-state q-p' space.
m	=	l/z = normalized breadth or foundation length in plan (Fadum's chart).

Terminology/Nomenclature (continued)

n	=	b/z = normalized width of foundation in plan view (Fadum's chart).
N_c	=	base bearing factor for cohesion term (undrained loading, short-term); shallow and deep
N_q	=	base bearing factor for overburden effect (drained, long-term); deep foundations
$N_($	=	base bearing factor for frictional resistance; shallow foundations (drained, long-term)
OCR	=	overconsolidation ratio = F_p'/F_{vo}'.
P_c'	=	preconsolidation stress, also designated $P_c' = \sigma_{vmax}' = \sigma_p'$
R_i	=	correction factors for pile settlement analyses via elastic theory. (R_k, R_n, R_b, R_h)
R	=	vectoral distance to point of interest in subsurface space = $(z^2+r^2)^{0.5}$
r	=	radial distance from center axis of foundation (cylindrical coordinates).
P	=	axial load (also given as Q).
p	=	= P/A_f = unit surface stress on foundation (also designated q).
p_u	=	ultimate stress from cavity expansion theory
p_a	=	reference stress = 1 atmosphere = 1 bar . 1 tsf . 1 kg/cm^2 . 100 kPa. Also, σ_{atm}
p_0	=	mean stress = $(\sigma_1+\sigma_2+\sigma_3)/3$
p_0'	=	mean effective stress = $(\sigma_1'+\sigma_2'+\sigma_3')/3$
p_u	=	ultimate lateral soil resistance.
Q	=	axial load or force (also designated P in some books).
Q_s	=	shaft component of axial load.
Q_b	=	end bearing or base component of axial load.
Q_{ult}	=	ultimate load
q	=	= Q/A_f = unit stress applied by foundation (also, designated as p).
q_c	=	measured cone tip resistance; should be always upgraded to the corrected value q_t
q_t	=	(total) cone tip stress; Note: all noted q_c should be replaced with q_t
q_{ult}	=	ultimate base bearing stress = Q/A_b at failure.
q_{allow}	=	allowable unit stress ($q_{ult/}$FS).
q_{app}	=	applied unit stress at top of foundation.
t	=	footing thickness.
s	=	foundation deflection or vertical displacement
s_u	=	undrained shear strength = c_u
U	=	degree of consolidation
u	=	horizontal displacement (sometimes, also designated * for deflection).
u	=	(total) porewater pressure
u_1, u_2	=	measured piezocone porewater pressures during penetration at face and shoulder, respectively. Also designated as u_t (tip) and u_b (behind tip).
u_0	=	hydrostatic porewater pressure (equilibrium conditions).
V_p	=	compression wave velocity
V_s	=	shear wave velocity
W	=	weight of foundation
w	=	vertical displacement (sometimes, also designated D)
x	=	distance in horizontal (transverse) direction (Cartesian coordinates).
y	=	distance in horizontal (longitudinal) direction (Cartesian coordinates).
z	=	distance in vertical direction (i.e., depth below ground surface).

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FORMAT FOR HOMEWORK ASSIGNMENTS

For **all homework assignments and examinations,** please use the following formats:

1. Document your work with your name and date on each page. Try and use only 4 or 5 single sheets of paper, if possible, in order to *Save The Trees.* Heavier (i.e., more pages) is not better.

2. Cite all necessary references to equations, theories, charts, tables, etc. for your own future documentation and authenticity of backup materials. A reference to "Mayne - Class Notes" is insufficient, as these notes change each year. Give specific reference to the method used. If in fact class notes must be cited, give the year and page number and other relevant information.

3. Please use spreadsheets (or other math programs) to conduct homeworks, especially those where graphs and figures can assist in presentation of results. Quattro , Excel, Mathcad, Maple, Mathematica, Lotus 1-2-3, Symphony all will be adequate for these purposes. Spreadsheets are particularly useful for delineating the subsurface environment into many sublayers for analysis. Be careful to use x-y graphs to plot results of data synthesis and equations, and not use the line graph option.

4. When graphing, use scaled axes (by hand or by computer). Use evenly numbered scales (i.e. 100, 200, 300 etc., and not irregular enumeration). Use dots or symbols for measured data; in contrast, show theoretical relationships by continuous lines. Use different dots (squares, circles, diamonds) of varying sizes and different colors and styles for lines (dashed, solid, dotted) to clearly show contrasts.

5. **SHOW ALL UNITS**. Be careful of units conversions and label all answers, graph axes, and tables with the correct units. Numbers without proper units are meaningless in today's world of engineering. It's also dangerous as someone may read different units into the answer.

6. Be judicious in your use of paper: Put more than one graph on a page. No need to show each graph or figure on a full page.

7. Round off to one/two/three significant places. Dol Not show answers to 10 decimal places (i.e., in foundation engineering, "the calculated settlement is 36.7845232241535 mm" is absurd! because the accuracy with natural materials is not there). Spend some time in the formatting of your spreadsheet

8. Be neat and prepare your work properly in an organized format for the professor or grader to examine. Take time to amend and "pretty-up" your document/spreadsheet. For instance, Greek symbols can be shown, boxed-in areas to highlight, and graphs can be annotated with comments.

9. State all assumptions made in arriving at your solution, if needed. In some cases, correlations are commonly used to evaluate certain parameters (i.e., unit weight or relative density). Cite the specific correlation used so that it is traceable back to support your calculations.

10. Feel free to mark on your computer output using pencil/pen, or highlighter to clarify where the final answers or key points are located.

11. All profiles of in-situ test data (or lab data) are shown with depth pointing **down**. On some spreadsheets, this may be overcome by showing depth on abscissa (x-axis) and variables on the ordinate axis (y-axis). In other spreadsheets, negative depth values may be used to promote downward plotting. Or get a new spreadsheet program or separate graphics package (i.e., CoPlot, SigmaPlot, Grapher, Surfer, ...) that gives more flexibility.

12. If uncertain, please feel free to talk with the lecturer and obtain clarification on those items that need additional details. Email communication is convenient means to solicit specific answers or comments.

Flow Chart to Assessing Geotechnical Problems