FOUNDATION DESIGN

PRINCIPLES AND PRACTICES

Third Edition

Donald P. Coduto William A. Kitch
Man-chu Ronald Yeung

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Preface

Publication of this third edition of *Foundation Design: Principles and Practices* comes twenty years after the 1994 release of the first edition. The original book, along with the second edition published in 2001, enjoyed widespread use among students, researchers, and practicing engineers both in the United States and abroad.

Two new co-authors, William A. Kitch and Man-chu Ronald Yeung, have collaborated with the original author, Donald P. Coduto, to produce this third edition. All three are professors at California State Polytechnic University, Pomona, and previously collaborated on a new edition of *Geotechnical Engineering: Principles and Practices*, which is the companion volume to this book.

WHAT IS NEW IN THIS EDITION

This new edition reflects advancements in theory and practice over the past thirteen years, constructive suggestions we have received from readers, as well as our experiences using the book as a text in our undergraduate and graduate level foundation engineering courses. As part of this update, some chapters have been deleted, others have been added, and much of the book has been reorganized. Nearly every page has some revisions.

The most substantive and pervasive changes are the increased emphasis on limit state design and the inclusion of load and resistance factor design (LRFD) in both the structural and geotechnical aspects of the analysis and design process. These changes reflect the broader use of limit state design in engineering practices, such as the AASHTO code in North America and other codes around the world. Allowable stress design (ASD) methods have been retained, as this method is still widely used. Other noteworthy changes include:

- A new chapter on uncertainty and risk in foundation engineering.
- Design procedures that place greater emphasis on the distinction between serviceability limit states and ultimate limit states.
- Improved coverage of auger piles, including a new chapter on axial load design, which reflects advancements in this technology.

- A completely revised chapter on pile dynamics with more in depth material on Wave Equation Analysis and a new section on pulse load testing.
- Better integration with widely available software. For example, the chapter on laterally loaded piles is now based on the assumption that the reader has access to lateral load analysis software.
- A new chapter on serviceability limit states in piles.
- New chapters on foundations in rocks and intermediate geomaterials and ground improvement.
- Many new and updated example problems and homework problems.

A complete solutions manual as well as PowerPoint slides of the various illustrations and tables may be downloaded from the Instructor's Resource Center located at www.pearsonhighered.com/Coduto. This material is provided solely for the use of instructors in teaching their courses and assessing student learning. All requests for instructor access are verified against our customer database and/or through contacting the requestor's institution. Contact your local sales representative for additional assistance or support.

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Our current and former students Gerald Aspiras, Brian Barnhart, Alejandro Irigoyen, Jiang Ly, Zachary Murray, Christopher Sandoval, and John Schober assisted with proofreading, problem solutions, and various insights from a student's perspective. Kevin Coduto assisted with file management and photo editing. Multiple drafts also were tested in the classroom at Cal Poly Pomona, and we appreciate our students' patience as we experimented with various methods of explaining different concepts, as well as their assistance in proofreading the text.

We appreciate the support from Holly Stark and Scott Disanno at Pearson, who made this project possible, as well as Pavithra Jayapaul and Shylaja Gattupalli at Jouve-India who provided excellent production support. Finally we thank our families for their patience as we devoted long hours to finishing this project.

Donald P. Coduto
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Claremont, California

Notation and Units of Measurement

There is no universally accepted notation in foundation engineering. However, the notation used in this book, as described in the following table, is generally consistent with popular usage.

Symbol	Description	Typical Units English	Typical Units SI	Defined in Chapter
A	Base area of foundation	ft^2	m^2	Ch 3
A_0	Initial cross-sectional area	in^2	mm^2	Ch 4
A_1	Cross-sectional area of column	in^2	mm^2	Ch 10
A_2	Base area of frustum	in^2	mm^2	Ch 10
A_c	Cross-sectional area of concrete	in^2	mm^2	Ch 10
A_f	Cross-sectional area at failure	in^2	mm^2	Ch 4
A_g	Gross cross-sectional area	in^2	mm^2	Ch 10
A_p	Area of an individual plate	ft^2	m^2	Ch 18
A_r	Rod surface area	ft^2	m^2	Ch 18
A_s	Steel area	in^2	mm^2	Ch 10
A_{tg}	Area of pile group tip	ft^2	m^2	Ch 15
A_{tr}	Area of transverse reinforcing steel	in^2	mm^2	Ch 10
a	CPT net area ratio	Unitless	Unitless	Ch 4
a	Hoek-Brown constant given by Equation 25.5	Unitless	Unitless	Ch 25
a_{unl}	Pile acceleration at the unloading point	g	g	Ch 19
a_θ	Factor in N_q equation	Unitless	Unitless	Ch 7
B	Width of foundation	ft & in	mm	Ch 3
B_b	Diameter at base of foundation	ft	m	Ch 16
B_e	Equivalent footing width	ft	m	Ch 8
B_g	Width of pile group	ft	m	Ch 15
B_q	CPT pore pressure ratio	Unitless	Unitless	Ch 4

B_s	Diameter of shaft	ft	m	Ch 16
B'	Effective foundation width	ft-in	m	Ch 6
b	Unit length	ft	m	Ch 10
b_0	Length of critical shear surface	in	mm	Ch 10
b_c, b_q, b_γ	Bearing capacity base inclination factors	Unitless	Unitless	Ch 7
b_w	Length of critical shear surface	in	mm	Ch 10
C	Capacity of a structural element	Varies	Varies	Ch 2
C_1	Depth factor	Unitless	Unitless	Ch 8
C_2	Secondary creep factor	Unitless	Unitless	Ch 8
C_3	Shape factor	Unitless	Unitless	Ch 8
C_A	Aging factor	Unitless	Unitless	Ch 4
C_B	SPT borehole diameter correction	Unitless	Unitless	Ch 4
C_c	Compression index	Unitless	Unitless	Ch 3
C_{OCR}	Overconsolidation correction factor	Unitless	Unitless	Ch 4
C_P	Grain size correction factor	Unitless	Unitless	Ch 4
C_R	SPT rod length correction	Unitless	Unitless	Ch 4
C_r	Recompression index	Unitless	Unitless	Ch 3
C_S	SPT sampler correction	Unitless	Unitless	Ch 4
C_s	Side friction coefficient	Unitless	Unitless	Ch 15
C_t	Toe coefficient	Unitless	Unitless	Ch 15
COV	Coefficient of variation of a random variable	Unitless	Unitless	Ch 2
c	Concrete cover or spacing between bars	in	mm	Ch 10
c	Factor in Engineering News Formula	in	mm	Ch 19
c	Wave velocity in pile	ft/s	m/s	Ch 19
c	Column or wall width	in	mm	Ch 10
c'	Effective cohesion	$\mathrm{lb/ft^2}$	kPa	Ch 3
c'_{adj}	Adjusted effective cohesion	$\mathrm{lb/ft^2}$	kPa	Ch 7
c_n	Depth to the neutral axis in beam bending	in	mm	Ch 10
c_T	Total cohesion	$\mathrm{lb/ft^2}$	kPa	Ch 3
D	Depth of foundation	ft & in	mm or m	Ch 3
D	Demand placed on a structural element	Varies	Varies	Ch 2
D	Dead load	Varies	Varies	Ch 5
D	Depth of socket embedment	ft	m	Ch 25
D	Disturbance factor	Unitless	Unitless	Ch 25
D_2	Distance from transducers to pile tip	ft	m	Ch 19
D_{50}	Grain size at which 50 percent is finer	–	mm	Ch 4
$D_{\min}$	Minimum required embedment depth	ft	m	Ch 22
D_r	Relative density	percent	percent	Ch 3
D_w	Depth from ground surface to groundwater table	ft	m	Ch 7
d	Effective depth	in	mm	Ch 10

d	Vane diameter	in	mm	Ch 4
d	Depth factor in Equation 25.15	Unitless	Unitless	Ch 25
d_b	Reinforcing bar diameter	in	mm	Ch 10
d_c, d_q, d_γ	Bearing capacity depth factors	Unitless	Unitless	Ch 7
E	A probabilistic event	NA	NA	Ch 2
E	Portion of steel in center section	Unitless	Unitless	Ch 10
E	Modulus of elasticity	lb/in^2	MPa	Ch 2
E	Earthquake load	Varies	Varies	Ch 5
E_0	Modulus at ground surface	lb/ft^2	kPa	Ch 8
E_{25}	Secant modulus	lb/ft^2	kPa	Ch 20
E_a	Energy lost in appurtenances during pile driving	ft-lb	Joules	Ch 19
E_c	Modulus of elasticity for concrete	lb/in^2	MPa	Ch 14
E_D	DMT modulus	lb/ft^2	kPa	Ch 4
E_h	Kinetic energy of hammer during pile driving	ft-lb	Joules	Ch 19
E_i	Deformation modulus of intact rock	k/in^2	MPa	Ch 25
E_l	Viscous energy lost in soil during pile driving	ft-lb	Joules	Ch 19
E_m	SPT hammer efficiency	Unitless	Unitless	Ch 4
E_m	Rock mass deformation modulus	k/in^2	MPa	Ch 25
E_p	Energy lost in pile during driving	ft-lb	Joules	Ch 19
E_r	Rated energy of pile hammer	ft-lb	Joules	Ch 19
E_s	Equivalent modulus of elasticity	lb/ft^2	kPa	Ch 8
E_s	Work done on soil during pile driving	ft-lb	Joules	Ch 19
E_s	Modulus of elasticity for steel	lb/in^2	MPa	Ch 14
E_u	Undrained modulus of elasticity	lb/ft^2	kPa	Ch 4
EI	Expansion index	Unitless	Unitless	Ch 27
e	Eccentricity	ft	m	Ch 6
e	Void ratio	Unitless	Unitless	Ch 3
e	Base of natural logarithms	2.7183	2.7183	–
e_0	Initial void ratio	Unitless	Unitless	Ch 3
e_a	Efficiency factor for appurtenance losses in pile driving	Unitless	Unitless	Ch 19
e_B	Eccentricity in the *B* direction	ft	m	Ch 6
e_h	Efficiency of pile driving hammer	Unitless	Unitless	Ch 19
e_L	Eccentricity in the *L* direction	ft	m	Ch 6
$e_{\max}$	Maximum void ratio	Unitless	Unitless	Ch 3
$e_{\min}$	Minimum void ratio	Unitless	Unitless	Ch 3
F	Factor of safety	Unitless	Unitless	Ch 2
F	Force applied in pile driving or dynamic testing	k	kN	Ch 19

F_a	Body force due to acceleration in dynamic testing	k	kN	Ch 19
F_d	Dynamic force applied in dynamic testing	k	kN	Ch 19
F_r	CPT normalized friction ratio	Unitless	Unitless	Ch 4
F_{unl}	Force in pile at the unloading point	k	kN	Ch 19
F_v	Damping force applied in dynamic testing	k	kN	Ch 19
f	Mobilized unit side friction resistance	$1b/ft^2$	kPa	Ch 14
f_a	Allowable axial stress	$1b/in^2$	MPa	Ch 21
f_b	Allowable flexural stress	$1b/in^2$	MPa	Ch 21
f_c'	28-day compressive strength of concrete	$1b/in^2$	MPa	Ch 10
f_n	Nominal unit side friction capacity	$1b/ft^2$	kPa	Ch 13
f_{pc}	Effective prestress on gross section	$1b/in^2$	MPa	Ch 21
f_s	CPT cone side friction	T/ft^2	MPa or kg/cm^2	Ch 4
f_v	Allowable shear stress	$1b/in^2$	MPa	Ch 21
f_y	Yield strength of steel	$1b/in^2$	MPa	Ch 10
G	Shear modulus	Unitless	Unitless	Ch 4
G_s	Specific gravity of solids	Unitless	Unitless	Ch 3
GSI	Geological Strength Index	Unitless	Unitless	Ch 25
g_c, g_q, g_γ	Bearing capacity ground inclination factors	Unitless	Unitless	Ch 7
H	Thickness of soil stratum	ft	m	Ch 3
H	Earth pressure load	Varies	Varies	Ch 5
H	Initial height of specimen immediately before soaking	in	mm	Ch 27
h	Hammer stroke	in	m	Ch 19
h	Expansion of soil	in	mm	Ch 27
h_0	Initial height of sample	in	mm	Ch 27
I	Moment of inertia	in^4	mm^4	Ch 21
I_c	CPT normalized soil behavior type index	Unitless	Unitless	Ch 4
I_D	DMT material index	Unitless	Unitless	Ch 4
I_E, I_F, I_G	Stress influence factors	Unitless	Unitless	Ch 8
I_P	Plasticity index	Unitless	Unitless	Ch 3
I_r	Rigidity index	Unitless	Unitless	Ch 15
I_ε	Strain influence factor	Unitless	Unitless	Ch 8
$I_{\varepsilon c}$	Strain influence factor for continuous foundation	Unitless	Unitless	Ch 8
$I_{\varepsilon p}$	Peak strain influence factor	Unitless	Unitless	Ch 8
$I_{\varepsilon s}$	Strain influence factor for square foundation	Unitless	Unitless	Ch 8
I_σ	Stress influence factor	Unitless	Unitless	Ch 3
I_0, I_1	Stress influence factors	Unitless	Unitless	Ch 8
i_c, i_q, i_γ	Bearing capacity load inclination factors	Unitless	Unitless	Ch 7

J_S	Smith damping factor	Unitless	Unitless	Ch 19
J_p	Pile damping factor	Unitless	Unitless	Ch 19
j_s	Soil damping factor	Unitless	Unitless	Ch 19
K	Coefficient of lateral earth pressure	Unitless	Unitless	Ch 3
K	Bulk modulus	Unitless	Unitless	Ch 4
K_0	Coefficient of lateral earth pressure at rest	Unitless	Unitless	Ch 3
K_a	Coefficient of active earth pressure	Unitless	Unitless	Ch 3
K_D	DMT horizontal stress index	Unitless	Unitless	Ch 4
K_E	Factor in Fleming method	Unitless	Unitless	Ch 20
K_p	Coefficient of passive earth pressure	Unitless	Unitless	Ch 3
K_s	Side resistance flexibility factor	Unitless	Unitless	Ch 20
K_{sp}	Empirical coefficient in Equation 25.15	Unitless	Unitless	Ch 25
K_t	Toe resistance flexibility factor	Unitless	Unitless	Ch 20
K_t	Coefficient of lateral earth pressure at ground surface	Unitless	Unitless	Ch 15
K_{tr}	Splitting term for development length	in	mm	Ch 10
k	Factor in computing depth factors	Unitless	Unitless	Ch 7
k_s	Coefficient of subgrade reaction	$1b/in^3$	kN/m^3	Ch 11
k_s	LCPC side friction factor	Unitless	Unitless	Ch 15
k_t	LCPC toe bearing factor	Unitless	Unitless	Ch 15
L	Length of foundation	ft-in	mm	Ch 3
L	Live load	Varies	Varies	Ch 5
L_F	Factor in Fleming method	ft	m	Ch 20
L_g	Length of pile group	ft	m	Ch 15
LL	Liquid limit (see w_L)	Unitless	Unitless	Ch 3
L_r	Live roof load	Varies	Varies	Ch 5
L'	Effective foundation length	ft-in	m	Ch 6
l	Cantilever distance	in	mm	Ch 10
l_d	Development length	in	mm	Ch 10
l_{dh}	Development length for hook	in	mm	Ch 10
M	Constrained modulus	$1b/ft^2$	kPa	Ch 4
M	Moment load	ft-k	kN-m	Ch 5
M_n	Nominal moment load capacity	ft-k	kN-m	Ch 10
M_s	Flexibility factor	Unitless	Unitless	Ch 20
M_u	Factored moment load	ft-k	kN-m	Ch 5
M_{uc}	Factored moment on the section being analyzed	in-lb	kN-m	Ch 10
m	Safety margin	Unitless	Unitless	Ch 2
m	Factor in computing load inclination factors	Unitless	Unitless	Ch 7
m_b	Hoek-Brown constant given by Equation 25.3	Unitless	Unitless	Ch 25

m_i	m_b for intact rock	Unitless	Unitless	Ch 25
m_v	Coefficient of compressibility	$ft^2/1b$	1/kpa	Ch 4
N	SPT blow count recorded in field	Blows/ft	Blows/ 300 mm	Ch 4
N	Nominal load capacity	Varies	Varies	Ch 5
N	Number of piles in a group	Unitless	Unitless	Ch 15
N_B	Becker blow count	Blows/ft	Blows/ 300 mm	Ch 4
N_w	Stress wave number	Unitless	Unitless	Ch 19
N_c, N_q, N_γ	Bearing capacity factors	Unitless	Unitless	Ch 7
N_c^*, N_q^*, N_γ^*, N_σ	Bearing capacity factors	Unitless	Unitless	Ch 15
N_u	Breakout factor	Unitless	Unitless	Ch 16
N_{cr}^*	Bearing capacity factor for rock	Unitless	Unitless	Ch 25
$N_{1,60}$	SPT blow count corrected for field procedures and overburden stress	Blows/ft	Blows/ 300 mm	Ch 4
N_{60}	SPT blow count corrected for field procedures	Blows/ft	Blows/ 300 mm	Ch 4
n	Porosity	percent	percent	Ch 3
n	CPT stress exponent	Unitless	Unitless	Ch 4
OCR	Overconsolidation ratio	Unitless	Unitless	Ch 3
P	Normal load	k	kN	Ch 5
$P(E)$	Probability of event, E	NA	NA	Ch 2
P_a	Allowable downward load capacity	k	kN	Ch 9
P_a	Active earth pressure resultant force	lb	kN	Ch 3
P_a	Atmospheric pressure	$1\ ton/ft^2$	100 kPa	Ch 4
$P_{a,up}$	Allowable upward load capacity	k	kN	Ch 13
P_{ag}	Allowable load capacity of pile group	k	kN	Ch 15
P_{up}	Upward load	k	kN	Ch 13
$P_{up,n}$	Nominal upward load capacity	k	kN	Ch 13
P_f	Probability of failure	Unitless	Unitless	Ch 2
P_f	Axial load at failure	lb	N	Ch 4
PI	Plasticity index (see I_P)	Unitless	Unitless	Ch 3
P_j	Final jacking force	k	kN	Ch 18
PL	Plastic limit (see w_P)	Unitless	Unitless	Ch 3
P_m	p multiplier	Unitless	Unitless	Ch 22
P_n	Nominal downward load capacity	k	kN	Ch 5
P_{nb}	Nominal column bearing capacity	k	kN	Ch 10
P_p	Passive earth pressure resultant force	lb	kN	Ch 3
P_s	Side friction resistance	k	kN	Ch 13

P_t	Toe bearing resistance	k	kN	Ch 13
P'_t	Net toe bearing resistance	k	kN	Ch 13
P_u	Factored normal load	k	kN	Ch 5
p	Lateral soil resistance per unit length of pile	lb	kN	Ch 22
p	Air pressure inside pneumatic caisson	lb/in^2	MPa	Ch 12
p_0, p_1	DMT pressure readings	lb/in^2	kPa	Ch 4
p_a	Atmospheric pressure	lb/in^2	kPa	Ch 16
p_u	Ultimate lateral soil resistance per unit length of pile	lb	kN	Ch 22
Q_c	Compressibility factor	Unitless	Unitless	Ch 4
Q_{tn}	CPT normalized cone tip resistance	Unitless	Unitless	Ch 4
q	Bearing pressure	lb/ft^2	kPa	Ch 6
q	Quake	in	mm	Ch 19
q'	Net bearing pressure	lb/ft^2	kPa	Ch 6
q'	Mobilized net unit toe bearing resistance	lb/ft^2	kPa	Ch 14
q_a	Allowable bearing capacity	lb/ft^2	kPa	Ch 7
q_A	Allowable bearing pressure	lb/ft^2	kPa	Ch 6
$q_{A,SLS}$	Allowable bearing pressure based on serviceability limit state	lb/ft^2	kPa	Ch 9
$q_{A,ULS}$	Allowable bearing pressure based on ultimate limit state	lb/ft^2	kPa	Ch 9
q_c	CPT cone resistance	T/ft^2	MPa or kg/cm^2	Ch 4
q_E	Effective cone resistance	T/ft^2	kg/cm^2 or MPa	Ch 15
q_{Eg}	Factor in Eslami and Fellenius method	T/ft^2	kg/cm^2 or MPa	Ch 15
q_{eq}	Equivalent bearing pressure	lb/ft^2	kPa	Ch 6
$q_{\max}$	Maximum bearing pressure	lb/ft^2	kPa	Ch 6
$q_{\min}$	Minimum bearing pressure	lb/ft^2	kPa	Ch 6
q_n	Nominal unit bearing capacity	lb/ft^2	kPa	Ch 7
q'_n	Nominal unit toe bearing capacity	lb/ft^2	kPa	Ch 13
q_t	Corrected SPT cone tip resistance	T/ft^2	MPa or kg/cm^2	Ch 4
q'_{tr}	Reduced net unit toe bearing resistance	lb/ft^2	kPa	Ch 15
q_u	Unconfined compressive strength	lb/ft^2	kPa	Ch 4
R	Reliability	Unitless	Unitless	Ch 2
R	Rain load	Varies	Varies	Ch 5
R	Total resistance of pile during driving	k	kN	Ch 19

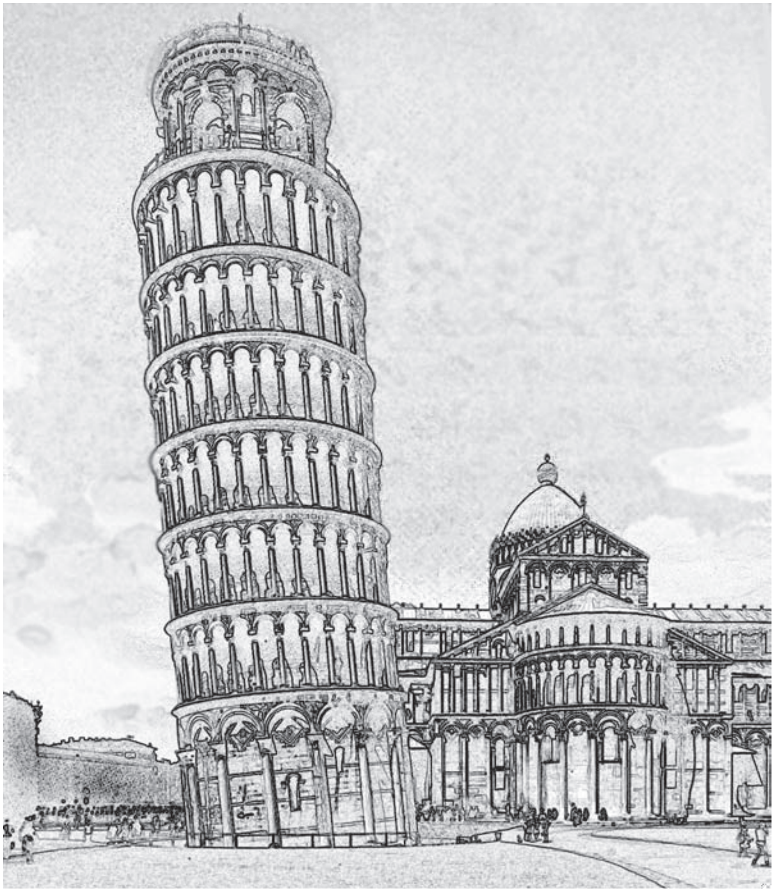
R_d	Dynamic resistance of pile during driving	Unitless	Unitless	Ch 19
R_f	Friction ratio in CPT	Unitless	Unitless	Ch 4
RMR	Rock Mass Rating	Unitless	Unitless	Ch 25
RQD	Rock quality designation	Unitless	Unitless	Ch 25
R_s	Static resistance of pile during driving	Unitless	Unitless	Ch 19
R_u	Ultimate static resistance of pile during driving	k	kN	Ch 19
R_{ur}	Required ultimate static resistance of pile during driving	k	kN	Ch 19
r	Rigidity factor	Unitless	Unitless	Ch 8
S	Snow load	Varies	Varies	Ch 5
S	Slope of pile from the vertical	radians	radians	Ch 22
S	Elastic section modulus	in^3	mm^3	Ch 21
S	Degree of saturation	percent	percent	Ch 3
S	Column spacing	ft	m	Ch 5
S_{mi}	Joint spacing of the ith discontinuity set	ft	m	Ch 25
SR	Spacing ratio	Unitless	Unitless	Ch 25
S_t	Sensitivity	Unitless	Unitless	Ch 3
s	Shear strength	lb/ft^2	kPa	Ch 3
s	Center-to-center spacing of piles or reinforcing bars	in	mm	Ch 15
s	Pile set	in	mm	Ch 19
s	Hoek-Brown constant given by Equation 25.4	Unitless	Unitless	Ch 25
s_c, s_q, s_γ	Bearing capacity shape factors	Unitless	Unitless	Ch 7
s_u	Undrained shear strength	lb/ft^2	kPa	Ch 3
s_v	Vertical spacing of discontinuity	ft	m	Ch 25
T	Thickness of foundation	ft-in	mm	Ch 10
T_f	Torque at failure	in-lb	N-m	Ch 4
TMI	Thornthwaite moisture index	Unitless	Unitless	Ch 27
t	Time	yr	yr	Ch 7
t	Factor in rock bearing formula	Unitless	Unitless	Ch 25
t_d	Aperture of discontinuity	in	mm	Ch 25
t_p	Wave propagation time in pile driving	s	s	Ch 19
t_{unl}	Time at which pile velocity is zero	s	s	Ch 19
U	Generic factored load	Varies	Varies	Ch 5
u	Displacement of pile or pile segment	in	mm	Ch 19
u	Pore water pressure	lb/ft^2	kPa	Ch 3
u_0	Equilibrium pore water pressure	lb/ft^2	kPa	Ch 4
u_2	Pore water pressure behind CPT cone	lb/ft^2	kPa	Ch 4
u_D	Pore water pressure at bottom of foundation	lb/ft^2	kPa	Ch 6

u_e	Excess pore water pressure	lb/ft^2	kPa	Ch 3
V	Shear load	k	kN	Ch 5
V_a	Allowable shear load capacity	k	kN	Ch 7
V_c	Nominal shear capacity of concrete	lb	kN	Ch 10
V_n	Nominal shear load capacity	k	kN	Ch 7
V_{nc}	Nominal shear capacity on critical surface	lb	kN	Ch 10
V_s	Nominal shear capacity of reinforcing steel	lb	kN	Ch 10
V_u	Factored shear load	k	kN	Ch 5
V_{uc}	Factored shear load on critical surface	lb	kN	Ch 10
V_v	Volume of voids	m^2	ft^2	Ch 3
v	Pile hammer impact velocity	in/s	m/s	Ch 19
v	Velocity of pile or pile segment	ft/s	m/s	Ch 19
W	Wind load	Varies	Varies	Ch 5
W_f	Weight of foundation	lb	kN	Ch 6
W_r	Hammer ram weight	lb	kN	Ch 19
w	Moisture content	percent	percent	Ch 3
w_L	Liquid limit	Unitless	Unitless	Ch 3
w_P	Plastic limit	Unitless	Unitless	Ch 3
w_s	Shrinkage limit	Unitless	Unitless	Ch 3
Y_{50}	Lateral deflection required to achieve one-half of the ultimate soil resistance	in	mm	Ch 22
y	Lateral deflection	in	mm	Ch 22
y_t	Lateral deflection at top of foundation	in	mm	Ch 22
Z_M	DMT gage zero offset pressure	lb/in^2	kPa	Ch 4
z	Depth below ground surface	ft	m	Ch 3
z	Settlement	in	mm	Ch 20
z_f	Depth below bottom of foundation	ft	m	Ch 3
z_i	Depth of the midpoint of the socket	ft	m	Ch 25
z_w	Depth below the groundwater table	ft	m	Ch 3
α	Wetting coefficient	Unitless	Unitless	Ch 27
α	Adhesion factor	Unitless	Unitless	Ch 15
α	Slope of footing bottom	deg	deg	Ch 7
α_M	Constrained modulus coefficient for CPT	Unitless	Unitless	Ch 4
α_P	Load sharing ratio	Unitless	Unitless	Ch 24
α_E	Joint modification factor	Unitless	Unitless	Ch 25
β	Modulus to shear strength ratio	Unitless	Unitless	Ch 4
β	Normalized modulus	Unitless	Unitless	Ch 8
β	Side friction factor in β method	Unitless	Unitless	Ch 15
β_0, β_1	Correlation factors for modulus based on SPT	Unitless	Unitless	Ch 4
β_z	Footing shape and rigidity factor	Unitless	Unitless	Ch 25

γ	Unit weight	lb/ft^3	kN/m^3	Ch 3
γ	Load factor	Unitless	Unitless	Ch 5
γ'	Buoyant unit weight	lb/ft^3	kN/m^3	Ch 2
γ'	Effective unit weight	lb/ft^3	kN/m^3	Ch 7
γ_b	Buoyant unit weight	lb/ft^3	kN/m^3	Ch 3
γ_c	Unit weight of concrete	lb/ft^3	kN/m^3	Ch 6
γ_d	Dry unit weight	lb/ft^3	kN/m^3	Ch 3
γ_w	Unit weight of water	lb/ft^3	kN/m^3	Ch 3
$\Delta\sigma_z$	Change in vertical stress	lb/ft^2	kPa	Ch 3
δ	Total settlement	in	mm	Ch 3
δ_a	Allowable total settlement	in	mm	Ch 5
δ_c	Consolidation settlement	in	mm	Ch 3
δ_D	Differential settlement	in	mm	Ch 5
δ_{Da}	Allowable differential settlement	in	mm	Ch 5
δ_d	Distortion settlement	in	mm	Ch 3
δ_e	Settlement due to elastic compression	in	mm	Ch 20
δ_s	Secondary compression settlement	in	mm	Ch 3
δ_s	Settlement due to mobilization of side friction	in	mm	Ch 20
δ_t	Settlement due to mobilization of toe bearing	in	mm	Ch 20
δ_t	Vertical displacement required to mobilize the full side friction resistance, assumed to be 25 mm (1 in)	in	mm	Ch 25
δ_{toe}	Displacement at pile toe	in	mm	Ch 20
δ_w	Heave or settlement due to wetting	in	mm	Ch 27
δ_z	Displacement at a point on the pile	in	mm	Ch 20
ε	Normal strain	Unitless	Unitless	Ch 3
ε_{50}	Axial strain at which 50 percent of the soil strength is mobilized	Unitless	Unitless	Ch 22
ε_a	Axial strain	Unitless	Unitless	Ch 4
ε_c	Hydrocollapse strain	Unitless	Unitless	Ch 28
ε_f	Strain at failure	Unitless	Unitless	Ch 4
ε_r	Radial strain	Unitless	Unitless	Ch 4
ε_t	Tensile strain in reinforcement	Unitless	Unitless	Ch 10
ε_w	Potential swell strain	Unitless	Unitless	Ch 27
ε_z	Vertical strain	Unitless	Unitless	Ch 3
η	Factor in Shields chart	Unitless	Unitless	Ch 7
η	Group efficiency factor	Unitless	Unitless	Ch 15
θ_a	Allowable angular distortion	radians	radians	Ch 5
λ	Factor in Shields chart	Unitless	Unitless	Ch 7
λ	Lightweight concrete factor	Unitless	Unitless	Ch 10

λ	Vane shear correction factor	Unitless	Unitless	Ch 4
λ_i	Frequency of the ith discontinuity set	ft^{-1}	m^{-1}	Ch 25
μ	Average or mean of a random variable	Unitless	Unitless	Ch 2
μ	Coefficient of friction	Unitless	Unitless	Ch 7
ν	Poisson's ratio	Unitless	Unitless	Ch 4
ν_m	Poisson's ratio of rock mass	Unitless	Unitless	Ch 25
ρ	Mass density	lb_m/ft^3	kg/m^3	Ch 19
ρ	Steel ratio	Unitless	Unitless	Ch 10
ρ_{min}	Minimum steel ratio	Unitless	Unitless	Ch 10
σ	Total stress	lb/ft^2	kPa	Ch 3
σ	Normal pressure imparted on a surface	lb/ft^2	kPa	Ch 3
σ	Standard deviation	Unitless	Unitless	Ch 2
σ'	Effective stress	lb/ft^2	kPa	Ch 3
σ'_1	Major effective principal stress at failure	lb/ft^2	kPa	Ch 25
σ'_3	Minor effective principal stress at failure	lb/ft^2	kPa	Ch 25
σ'_c	Preconsolidation stress	lb/ft^2	kPa	Ch 3
σ_{ci}	Uniaxial compressive strength of the intact rock	k/in^2	MPa	Ch 25
σ'_h	Horizontal stress	lb/ft^2	kPa	Ch 25
σ'_m	Preconsolidation margin	lb/ft^2	kPa	Ch 3
σ_n	Fluid pressure exerted by the concrete in socket during placement	lb/ft^2	kPa	Ch 25
σ_p	Representative passive pressure	lb/ft^2	kPa	Ch 3
σ_s	Swell pressure	lb/ft^2	kPa	Ch 27
σ_t	Threshold collapse stress	lb/ft^2	kPa	Ch 28
σ_x	Horizontal total stress	lb/ft^2	kPa	Ch 3
σ'_x	Horizontal effective stress	lb/ft^2	kPa	Ch 3
σ_z	Vertical total stress	lb/ft^2	kPa	Ch 3
σ'_z	Vertical effective stress	lb/ft^2	kPa	Ch 3
σ'_{z0}	Initial vertical effective stress	lb/ft^2	kPa	Ch 3
σ_{zD}	Vertical total stress at depth *D* below the ground surface	lb/ft^2	kPa	Ch 7
σ'_{zD}	Vertical effective stress at depth *D* below the ground surface	lb/ft^2	kPa	Ch 7
σ'_{zf}	Final effective stress	lb/ft^2	kPa	Ch 3
σ'_{zp}	Initial vertical effective stress at depth of peak strain influence factor	lb/ft^2	kPa	Ch 8
$\Phi(x)$	Cumulative distribution function for the standard normal distribution	Unitless	Unitless	Ch 2
ϕ	Resistance factor	Unitless	Unitless	Ch 5
ϕ'	Effective friction angle	deg	deg	Ch 3
ϕ'_{adj}	Adjusted effective friction angle	deg	deg	Ch 7

ϕ_f	Soil-foundation interface friction angle	deg	deg	Ch 15
ϕ_{rc}	Socket wall interface friction angle, assumed to be 30 degrees	deg	deg	Ch 25
ϕ_T	Total friction angle	deg	deg	Ch 3
ψ	Factor in Shields chart	Unitless	Unitless	Ch 7
ψ_e	Coating factor for computing development length	Unitless	Unitless	Ch 10
ψ_s	Reinforcement size factor for computing development length	Unitless	Unitless	Ch 10
ψ_t	Location factor for computing development length	Unitless	Unitless	Ch 10
Ω	Probability or sample space	NA	NA	Ch 2
ω	Tilt of a structure	Unitless	Unitless	Ch 5



Part A

General Principles

1

Foundations

> ***The foundations are properly called the basis of the fabrick, viz. that part of it under ground which sustains the whole edifice above; and therefore of all the errors that can be committed in building, those made in the foundation are most pernicious, because they at once occasion the ruin of the whole fabrick, nor can they be rectified without the utmost difficulty.***
>
> Venetian architect Andrea Palladio (1508–1580)
> as translated by Isaac Ware, 1738

Builders have long recognized the importance of a solid foundation, and that the integrity of a structure can be no greater than that of its foundation. If a foundation fails, the overlying structure fails with it. These truths were especially evident in Palladio's renaissance Venice, where heavy masonry structures were being built on small islands in a lagoon underlain by very soft soils. In addition, as Palladio observed, defects in the foundation are very difficult to repair after the structure has been built. Thus, well-designed and well-constructed foundations continue to be an essential part of successful construction.

However, foundations can also be very expensive, so over-designed foundations are needlessly wasteful and inefficient. Our goal is to provide sturdy foundations that properly support the superstructure, while avoiding costly over-design. The methods of doing so form the subject of this book.

1.1 FOUNDATION CLASSIFICATION

Foundations are structural elements that transfer loads from the superstructure to the underlying soil or rock. A structure may be supported on a system of individual foundations, or on a single large foundation. Engineers classify foundations into two broad categories: *shallow foundations* and *deep foundations*, as shown in Figure 1.1.

Shallow foundations transmit the structural loads to the soils immediately beneath the foundation, and are discussed in Chapters 6 to 11. The most common type is a *spread footing*, which spreads the applied load over a sufficiently large area to maintain soil stresses within tolerable limits. Spread footings are easy and inexpensive to build, and are most often used to support small to medium size structures on sites with good soil conditions. Typically, each column has its own spread footing, although sometimes multiple closely-spaced columns are supported on a single footing. Thus, a building might have dozens of individual footings.

The second type of shallow foundation is a *mat foundation* (also called a *raft foundation*), which normally encompasses the entire footprint of the structure. Mats have the advantage of providing structural continuity and rigidity, as well as spreading the load over a larger area.

Conversely, deep foundations transmit much, or all, of the applied load to deeper soils, and are discussed in Chapters 12 to 24. *Piles* are long slender structural members that can be either prefabricated and driven into the ground, or cast in place. *Caissons* are large prefabricated boxes that are sunk into place and filled with concrete to form a foundation. The load-carrying capacity of soils generally increases with depth, and deep foundations engage a larger volume of soil, so they are most often used on larger and heavier structures, especially when the shallow soils are poor.

The terminology used to describe and classify foundations is sometimes inconsistent. Different terms are sometimes used to describe the same thing, and the same term is sometimes used to describe different things. Even the term "foundation" is sometimes used to describe the underlying soil or rock rather than a structural element. This book uses terminology that reflects common practice, and alternative terms are included in context.

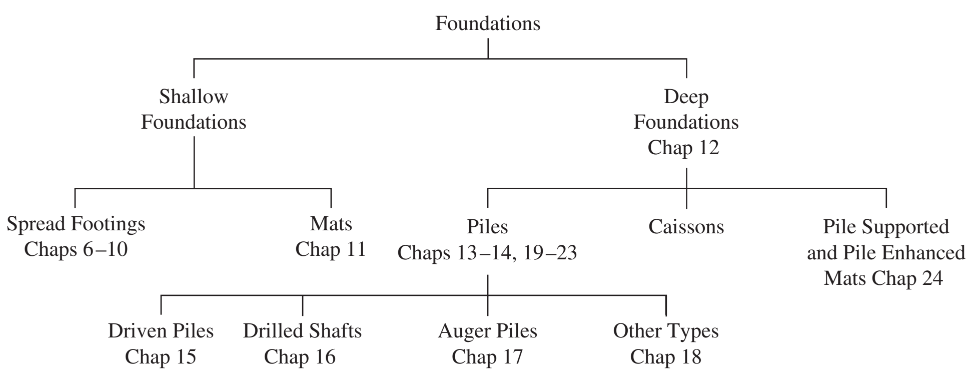


Figure 1.1 Classification of foundations.

1.2 THE EMERGENCE OF MODERN FOUNDATION ENGINEERING

The history of foundations extends for thousands of years, and impressive projects were built hundreds or even thousands of years ago. For example, 4,000 to 5,000 years ago the alpine lake dwellers in Europe used timber piles to support their houses. Also, in the year 55 BCE, Julius Caesar built a pile-supported bridge across the Rhine River to facilitate his conquest of Gaul. In Shanghai, the 40 m tall Longhua Pagoda was constructed on soft clay in 977 CE using a foundation of bricks laid on a wooden raft supported by closely-spaced wooden piles, a design very similar to today's pile-supported mat, and has stood firm for over 1,000 years while some newer buildings nearby have been badly damaged by excessive settlement (Kerisel, 1987).

Early foundation designs were based on precedent, intuition, and common sense. Through trial-and-error, builders developed rules for selecting, sizing, and constructing foundations. For example, even as late as the nineteenth century, the width of spread footings supporting masonry walls in New York City was set at 1.5 times the width of the wall when founded on compact gravel, and 3.0 times the width of the wall when founded on sand or stiff clay (Powell, 1884).

These empirical rules, combined with good judgment, usually produced acceptable results as long as they were applied to structures and soil conditions similar to those encountered in the past. However, the results were sometimes disastrous when builders extrapolated the rules to new conditions. This problem became especially troublesome when new building materials and methods of construction began to appear during the last quarter of the nineteenth century. The introduction of steel and reinforced concrete led to a gradual transition away from rigid masonry structures supported primarily on bearing walls to more flexible frame structures that used columns. These new materials also permitted structures to be taller and heavier than before. In addition, as good sites became increasingly scarce, builders were forced to consider sites with poorer soil conditions, which made foundation design and construction much more difficult. Thus, the old rules for foundation design no longer applied.

The introduction of these new building materials led to more rational design methods, the beginning of what we now call structural engineering, and this rational approach naturally extended to the foundations. Geotechnical engineering, which began in earnest during the 1920s, further added to our understanding of foundations and the mechanical processes of transferring loads into the ground. Thus, instead of simply developing new empirical rules, engineers began to investigate the behavior of foundations and develop more rational methods of design, establishing the discipline of foundation engineering. This transition began in the late nineteenth century, rapidly progressed through the twentieth century, and continues in the twenty-first century.

These advances in analysis and design were accompanied by tremendous improvements in construction methods and equipment. For example, modern pile driving hammers enable construction of huge high-capacity piles that far exceed the capabilities of timber piles driven by falling weights. These advances have enabled building at sites where foundation construction had previously been impossible or impractical.

It is now possible to build reliable, cost-effective, high-capacity foundations for a wide range of modern structures, even on very difficult sites. Advances in design and construction continue to be developed in the twenty-first century, so future engineers will probably have even greater capabilities. Nevertheless, precedent, empiricism, common sense, and engineering judgment are still important, and continue to have a role in modern foundation engineering.

The Eiffel Tower

The Eiffel Tower, Figure 1.2, is an excellent example of a new type of structure in which the old rules for foundations no longer applied. It was built for the Paris Universal Exposition of 1889 and was the tallest structure in the world. Alexandre Gustave Eiffel, the designer and builder, was very conscious of the need for adequate foundations, and clearly did not want to create another Leaning Tower of Pisa (Kerisel, 1987).

The Eiffel Tower is adjacent to the Seine River, and is underlain by difficult soil conditions, including uncompacted fill and soft alluvial soils. Piers for the nearby Pont de l'Alma (Alma bridge), which were founded in this alluvium, had already settled nearly 1 m. The tower could not tolerate such settlements.

Figure 1.2 Two legs of the Eiffel Tower are underlain by softer soils, and thus could have settled more than the other two. Fortunately, Eiffel carefully explored the soil's conditions, recognized this potential problem, and designed the foundations to accommodate these soil conditions. His foresight and diligence resulted in a well-designed foundation system that has not settled excessively (Courtesy by Shutterstock).

Eiffel began exploring the subsurface conditions using the crude drilling equipment of the time, but was not satisfied with the results. He wrote: "What conclusions could one reasonably base on the examination of a few cubic decimeters of excavated soil, more often than not diluted by water, and brought to the surface by the scoop?" (Kerisel, 1987). Therefore, he devised a new means of exploring the soils, which consisted of driving a 200 mm diameter pipe filled with compressed air. The air kept groundwater from entering the tube, and thus permitted recovery of higher quality samples.

Eiffel's studies revealed that the two legs of the tower closest to the Seine were underlain by deeper and softer alluvium, and were immediately adjacent to an old river channel that had filled with soft silt. The foundation design had to accommodate these soil conditions, or else the two legs on the softer soils would settle more than the other two, causing the tower to tilt toward the river.

Based on his study of the soil conditions, Eiffel placed the foundations for the two legs furthest from the river on the shallow but firm alluvial soils. The bottoms of these foundations were above the groundwater table, so their construction proceeded easily. However, he made the foundations for the other two legs much deeper so they too were founded on firm soils. This required excavating about 12 m below the ground surface (6 m below the groundwater table). As a result of Eiffel's diligence, the foundations have safely supported the tower for more than a century, and have not experienced excessive differential settlements.

Chicago

The advancement of foundation engineering in Chicago also illustrates many of the worldwide changes in practice that occurred during the late nineteenth and early twentieth centuries (Peck, 1999). Rapid population growth and other factors drove a sustained construction boom that, in many ways, made the city a laboratory for new design and construction methods. Chicago is particularly interesting from a geotechnical perspective, because the city is underlain by saturated clay to a depth of about 100 ft. This is a stark contrast to New York City, where competent bedrock is often easily within reach and provides adequate bearing for the large buildings in most of Manhattan.

During the early part of this period, virtually all buildings in Chicago were comparatively small and supported on spread footings. This foundation type continued to be used as the size and weight of buildings increased. A significant advance came in 1873 when Frederick Baumann, a Chicago architect, published the pamphlet *The Art of Preparing Foundations, with Particular Illustration of the "Method of Isolated Piers" as Followed in Chicago* (Baumann, 1873). He appears to be the first to explicitly recommend that the base area of a footing should be proportional to the applied load, and that the loads should act concentrically upon the footing. He also gave allowable bearing pressures for Chicago soils and specified tolerable limits for total and differential settlements.

As buildings became increasingly larger and heavier, foundation settlement became increasingly problematic. The auditorium building, constructed between 1887 and 1889 on spread footings, is one of the most noteworthy examples. Most of the building had a height of 10 stories, but part of it consisted of a 19-story tower, as shown in Figure 1.3.

Figure 1.3 The auditorium building in Chicago experienced 28 in of settlement, but is still in service more than a century after its completion. This structure helped usher in new foundation designs that are less susceptible to settlement.

Although designed according to the state of the art at the time, the tower portion ultimately settled 28 in, with significant differential settlements between the tower and the less heavily loaded areas.

It became clear that spread footings were not adequate for larger buildings, even when designed according to Baumann's guidelines. Driven piles were then used on some buildings, but a new method, the Chicago caisson,[1] was introduced in 1892 by William

[1] In this case, the term "caisson" is being used to describe a foundation that we would classify as a cast-in-place pile. This is quite different from our usage of the term, which describes a method that uses large prefabricated boxes that are sunk into place and filled with concrete.

Sooy-Smith, a former civil war general turned foundation engineer. This method consisted of hand-excavating a cylindrical hole about 1 m in diameter down to harder bearing stratum, then filling the hole with cast-in-place concrete. Local engineers developed methods of designing and building these caissons, which solved the excessive settlement problem and soon became the foundation of choice. Modern high-rise buildings in Chicago, such as the Willis Tower (formerly known as the Sears Tower), still use drilled shafts, which are modern machine-dug versions of the Chicago caisson.

San Francisco–Oakland Bay Bridge

The original San Francisco–Oakland Bay Bridge, constructed between 1933 and 1936, required innovative foundations because of the poor soils conditions and deep water (Husband, 1936). For example, the foundation for one of the piers on the west span extends through an unprecedented 21 m (70 ft) of water, then 43 m (140 ft) of soil (much of it soft clay) to bedrock. This was far too deep for pneumatic caissons, which were the standard method of the day, so legendary foundation engineer Daniel Moran (1864–1937) was retained to help develop new technologies for building these foundations.

Based on Moran's work, several of the piers on both spans were constructed using a new type of massive caisson constructed of concrete and steel in a nearby shipyard. Initially airtight, the caisson was floated to the site, then accurately positioned in place on the bay floor by slowly filling its chambers with water. The underlying soil was then progressively excavated through the chambers using clamshell buckets until reaching the required depth. The caisson was then filled with concrete. In contrast, portions of the bridge near the Oakland shore were in much shallower water and had much shorter spans, so the piers were supported on groups of driven timber piles.

The eastern span was subsequently replaced with a new bridge, which was completed in 2013. Advances in heavy marine driven pile technology over the intervening 80 years, much of which was developed for offshore drilling platforms, resulted in a completely different foundation system. The new bridge is supported on 1.8 to 2.5 m (6–8 ft) diameter steel pipe piles driven with an exceptionally large hydraulic pile hammer to depths of 60 to 100 m (200–330 ft) (Saba et al., 2004). A total of 160 piles were used on the entire project.

1.3 THE FOUNDATION ENGINEER

Foundation engineering does not fit completely within any of the traditional civil engineering subdisciplines. Instead, the foundation engineer must be multidisciplinary and possess a working knowledge in each of the following areas:

- **Structural engineering**—A foundation is a structural member that must be capable of transmitting the applied loads, so we must also understand the principles and practices of structural engineering. In addition, the foundation supports a structure, so we must understand the sources and nature of structural loads and the structure's tolerance of foundation movements.

- **Geotechnical engineering—**All foundations interact with the ground, so the design must reflect the engineering properties and behavior of the adjacent soil and rock. Thus, the foundation engineer must understand geotechnical engineering. Most foundation engineers also consider themselves to be geotechnical engineers.
- **Construction engineering—**Finally, foundations must be built. Although the actual construction is performed by contractors and construction engineers, it is very important for the design engineer to have a thorough understanding of construction methods and equipment to develop a design that can be economically built. This knowledge also provides essential background when solving problems that develop during construction.

This book focuses primarily on the design of foundations, and thus emphasizes the geotechnical and structural engineering aspects. Discussions of construction methods and equipment are generally limited to those aspects that are most important to design engineers. Other important aspects of foundation construction which are primarily of interest to contractors are beyond the scope of this book.

1.4 CODES, STANDARDS, AND TECHNICAL LITERATURE

Foundation design and construction is subject to the provisions of various codes, which define the methods for computing applied loads, the load-carrying capacity of various structural materials, performance requirements, detailing requirements, and other aspects. Some of these provisions are similar to those that apply to other structural members, while others are unique to foundations. Most codes have a separate chapter specifically addressing foundations.

Codes are legally binding, and thus must be followed. The two most commonly used codes in the United States are:

- The International Building Code (IBC), which governs the design of most buildings (ICC, 2012). This code replaced the American model building codes (the Uniform Building Code, the National Building Code, and the Standard Building Code) as well as many local codes. The IBC has legal authority only when adopted by a state, city, or other regulatory authority, and these authorities sometimes include modifications. For example, building construction in California is governed by the California Building Code, which is a modified version of the IBC. Although the IBC and its variants is by far the most commonly used building code in the United States, some parts of the country use different codes. For example, the City of Chicago has its own unique building code.
- AASHTO *LRFD Bridge Design Specifications* (AASHTO, 2012) governs the design of highway structures. The American Association of State Highway and Transportation Officials is a consortium of the various state departments of transportation (DOTs), and thus has substantial influence on state DOT construction projects, as well as those for local governments. These state and local agencies