FOUNDATION ENGINEERING FOR EXPANSIVE SOILS

JOHN D. NELSON | KUO CHIEH CHAO
DANIEL D. OVERTON | ERIK J. NELSON

WILEY

Foundation Engineering for Expansive Soils

John D. Nelson
Kuo Chieh (Geoff) Chao
Daniel D. Overton
Erik J. Nelson

WILEY

Cover image: Adrian Morgan
Cover design: Cracked wall © man_kukuku/Thinkstock; all other images courtesy Engineering Analytics, Inc.

This book is printed on acid-free paper.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

Library of Congress Cataloging-in-Publication Data:

Nelson, John D.
Foundation engineering for expansive soils / John D. Nelson [and 3 others].
1 online resource.
Includes index.
Description based on print version record and CIP data provided by publisher; resource not viewed.
ISBN 978-1-118-41799-7 (pdf) – ISBN 978-1-118-41529-0 (epub) – ISBN 978-0-470-58152-0 (hardback)
1. Soil-structure interaction. 2. Swelling soils. 3. Foundations. I. Title.
TA711.5
624.1'51–dc23

2014043883

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Foundation Engineering for Expansive Soils

Preface

The practice of foundation engineering was first developed to address problems associated with settlement due to saturated soils that were prevalent in areas with soft coastal and deltaic deposits. As population and business centers moved into areas with more arid climates, problems with other types of soils became evident. Some soils that were capable of supporting a load in a natural unsaturated state were observed to either expand or collapse when wetted. These soils did not conform to the classical theories of soil mechanics and foundation engineering, and more research began to focus on the behavior of unsaturated soils.

Within the general category of unsaturated soils, the expansive soils posed the greatest problems, and created the most financial burden. In response to major infrastructure development in the late 1950s and 1960s there was an upswing in research regarding the identification of expansive soils and factors influencing their behavior. Engineers became more cognizant of the need for special attention to the unique nature of expansive soils.

The general curricula taught at universities did not specifically address the design of foundations for these soils, and engineers did not become aware of expansive soils unless they began to practice in areas where those soils existed. Therefore, the practice of foundation engineering for expansive soils developed around experience and empirical methods.

Few books have been written specifically on the subject of design of foundations on expansive soils. Fu Hua Chen wrote a book entitled *Foundations on Expansive Soils* that was published in 1975. A second edition of that book was published in 1988. Those books were based to a large extent on Mr. Chen's personal experiences along the Front Range of Colorado. The Department of the Army published a technical manual in 1983 titled, *Foundations for Expansive Soils*. That manual served as the basis for the design of structures on military bases, and was available to the civilian engineering community as well.

At about that same time the US National Science Foundation funded a research project at Colorado State University (CSU) dealing with expansive soils. The scope of that project included a survey of the practices followed by engineers throughout the United States and Canada, as well as individuals from other countries. On the basis of that survey, and research that had been conducted by that time, Nelson and Miller (1992) published a book entitled *Expansive Soils: Problems and Practices in Foundation and Pavement Engineering*.

In 1993 Fredlund and Rahardjo published their text, *Soil Mechanics for Unsaturated Soil*. That book extended the framework of classical soil mechanics to incorporate soil suction as an independent stress state variable, and provided the rigor needed for a theoretical understanding of unsaturated soils. A part of that book was devoted to the mechanics of expansive soil.

In the 20 years since the publication of Nelson and Miller (1992), the authors of this book have worked together and have performed hundreds of forensic investigations on expansive soils. In the course of that work, many new ideas have emerged, additional research has been conducted, and methods of analyses were developed that have been applied to foundation design. This book reflects the authors' experiences over the period since the book by Nelson and Miller was written. It incorporates a broader scope of analysis and a greater degree of rigor than the earlier work.

In a presentation at the 18th International Conference on Soil Mechanics and Geotechnical Engineering in which he introduced his most recent book, *Unsaturated Soil Mechanics in Engineering Practice*, Dr. Fredlund noted the need for practitioners to continue to publish works that will extend the application of the concepts of unsaturated soil mechanics to the solution of practical geotechnical engineering problems. It is believed that this book responds to that call and will provide a sound basis on which to establish a practice of foundation engineering for expansive soils.

Many people have contributed to the completion of this book, most notably Ms. Georgia A. Doyle. She has read the entire manuscript, provided necessary and valuable editing and coordination, and queried the authors where material was not clear. Many valuable comments were received from Dr. Donald D. Runnells after his review of chapter 2, and Dr. Anand J. Puppala after his review of chapter 10. Professor Erik. G. Thompson developed the FEM analysis for the APEX program presented in chapter 12.

In addition, many current and former staff of the authors' company, Engineering Analytics, Inc., have contributed in one way or another. Special recognition goes to Kristle Beaudet, Todd Bloch, Denise Garcia, Debbie Hernbloom, Jong Beom Kang, Lauren Meyer, Ronald Pacella, and Rob Schaut. Their help along the way is much appreciated.

John D. Nelson
Kuo Chieh (Geoff) Chao
Daniel D. Overton
Erik J. Nelson

List of Symbols

A_c	clay activity
B	width of footing
B	slope of matric suction vs water content curve
c	cohesion of soil
C	molar concentration
C_c	compression index
C_{DA}	"Department of Army" heave index
C_H	heave index
C_h	suction compression index
C_m	matric suction index
C_p	peak cohesion
C_r	residual cohesion
C_s	swelling index
C_t	compression index with respect to net normal stress
C_w	CLOD index
$C(\psi)$	correction function
d	distance between particles
d	pier shaft diameter
D	constrained modulus of soil
D_0	depth of nonexpansive fill
e	void ratio
e	base of natural logarithm, 2.71828
e_0	initial void ratio
E_s	Young's modulus of the soil
E_A	Young's modulus of the soil in units of bars
f	lateral restraint factor
f_s	anchorage skin friction
f_u	uplift skin friction
F_t	nodal force tangent to pier

F_t	maximum interior tensile force
g	gravitational acceleration
G_s	specific gravity of solids
h	pressure head
h_d	displacement pressure head
h_m	matric suction head
h_o	osmotic pressure head
H	thickness of a layer of soil
ΔH	change in thickness of that layer due to heave
H_t	total hydraulic head
i	hydraulic head gradient
I_{pt}	instability index
I_{ss}	shrink swell index
k	spring constant in APEX
K_a	active earth pressure
$K(h)$	coefficient of unsaturated hydraulic conductivity
K_0	coefficient of earth pressure at rest
K_p	passive earth pressure
K_s	coefficient of permeability
L	length of pier
L_{reqd}	required pier length
LL	liquid limit
$\Delta L/\Delta L_D$	linear strain relative to dry dimensions
m	molality
m	factor for swelling pressure correlation
n	porosity of the soil
p_a	active earth pressure
pF	unit for soil suction
p_0	equivalent fluid pressure
p_p	passive earth pressure
P	partial pressure of pore water vapor
P	load per linear dimension
P	footing load
P/P_0	relative humidity
P_{dl}	dead load on footing
PI	plasticity index
PL	plastic limit
P_{max}	maximum tensile force
P_0	saturation pressure of water vapor over a flat surface of pure water at the same temperature
P_0	total load due to earth pressure

q	flow rate of water
q	distributed load
q_a	allowable bearing pressure
q_u	unconfined compressive strength
q_m	mean rate of infiltration at the ground surface
r	radius
r^2	correlation coefficient
r_w	sources or sinks of water
R	universal gas constant
R	resistance force
RF	risk factor
RF_w	weighted risk factor
R_p	pullout capacity of helical bearing plate
s	coefficient for load effect on heave
S	degree of saturation
$\%SP$	percent of swelling pressure that is applied by the total applied stress on the soil
T	absolute temperature
T_s	surface tension
u_a	pore air pressure
$(u_a)_d$	displacement air entry pressure
u_w	pore water pressure
U	total uplift force
U_t	nodal displacement tangent to pier
V	molar volume of a solution
V	total volume of soil
$\Delta V/V$	volumetric strain
V_w	volume of water in an element of soil
w	gravimetric water content
w_{aev}	air entry gravimetric water content
w_u	gravimetric water content corresponding to a suction of 1 kPa
w_e	weight of sample at equilibrium
w_s	weight of oven-dry sample
y_{max}	differential soil movement
y_s	net ground surface movement
z	depth
z	elevation head
z	soil layer thickness
z_A	depth of active zone
z_{AD}	depth of design active zone

z_p	depth of potential heave
z_s	zone of seasonal moisture fluctuation
z_w	zone (depth) of wetting
z_{wt}	height above the water table
Δz	thickness of soil layer
α	compressibility factor
α	soil to pier adhesion factor
α	drainage slope
α_1	coefficient of uplift between the pier and the soil
α_2	coefficient of anchorage between the pier and the soil
β	contact angle with tube
β	reduction factor for expansive earth pressure
γ	unit weight of soil
γ_d	dry density of soil
γ_{sat}	saturated unit weight of soil
γ_t	total unit weight of soil
γ_w	unit weight of water
$\gamma_{\psi o}$	osmotic suction volumetric compression index
γ_σ	mean principal stress volumetric compression index
$\gamma_{\psi m}$	matric suction volumetric compression index
δ	interface friction angle
δ_{max}	differential heave
ε	strain
ε_{iso}	isotropic swelling strain
ε_s	strain
ε_{sn}	shrinking strain
ε_{sw}	swelling strain
ε_T	total range of strain
$\varepsilon_{s\%}$	percent swell
$\varepsilon_{s\%N}$	normalized percent swell
$\varepsilon_{s\%vo}$	percent swell measured from a sample inundated at the overburden stress in the consolidation-swell test
θ	volumetric water content
θ_f	volumetric water content above the wetting front
θ_r	residual volumetric water content
θ_s	saturated volumetric water content
λ	pore size distribution index
ν	number of ions from one molecule of salt
ν	Poisson's ratio
ρ	heave

$\Delta\rho$	differential movement
ρ_{max}	maximum heave
ρ_0	free-field heave
ρ_p	pier heave
ρ_s	solute mass/density
ρ_{ult}	total heave
$\sigma = (\sigma' + u_w)$	total stress, normal stress
$\sigma' = (\sigma - u_w)$	effective stress
$\sigma'' = (\sigma - u_a)$	net normal stress
σ''_{cs}	consolidation-swell swelling pressure
σ''_{cv}	constant volume swelling pressure
σ''_{cvN}	reduced swelling pressure
σ_{ext}	external stress
σ''_f	final vertical stress
σ''_h	lateral stress
σ''_i	inundation stress
σ_{int}	internal stress between particles
$\Delta\sigma''_v$	increment of applied stress
$\sigma_{vo}, \sigma'_{vo}, \sigma''_{vo}$	vertical overburden stress in terms of total, effective, or net normal stress
τ	shear stress
ϕ	osmotic coefficient
ϕ	angle of internal friction
ϕ_p	peak angle of internal friction
ϕ_r	residual angle of internal friction
χ	chi parameter
ψ	total suction
ψ_{ae}	air entry soil suction
$\psi_m = (u_a - u_w)$	matric suction
ψ_o	osmotic suction
ψ_r	residual suction

List of Abbreviations

APEX	analysis of piers in expansive soils
ANN	artificial neural network
CEAc = CEC/clay content	cation exchange capacity activity
CEC	cation exchange capacity
CNS	cohesive non-swelling
COLE	coefficient of linear extensibility
CS	consolidation-swell
CV	constant volume
DTA	differential thermal analysis
EI	expansion index
ET	evapotranspiration
FSI	free swell index
LE	linear extensibility
LMO	lime modification optimum
PVC	potential volume change
PVC	polyvinyl chloride
PVR	potential vertical rise
SAMC	standard absorption moisture content
SI	shrinkage index
SL	shrinkage limit
SSA	specific surface area
SWCC	soil water characteristic curve
SWCR	soil water characteristic relationship
TP	total potassium
UV	ultraviolet
XRD	X-ray diffraction

Contents

Preface / xv
List of Symbols / xix
List of Abbreviations / xxv

1. INTRODUCTION / 1

1.1 Purpose / 2
1.2 Organization / 2
1.3 Terminology / 4
References / 7

2. NATURE OF EXPANSIVE SOILS / 9

2.1 Microscale Aspects of Expansive Soil Behavior / 9
2.1.1 The Clay Particle / 10
2.1.1.1 Mineral Composition / 10
2.1.1.2 Interlayer Bonding / 12
2.1.1.3 Isomorphous Substitution and Surface Charges / 13
2.1.2 Adsorbed Cations and Cation Hydration / 15
2.1.3 The Clay Micelle / 17
2.1.4 Crystalline and Osmotic Expansion / 19
2.1.5 Effect of Mineralogy on Plasticity of Soil / 21
2.1.6 Effect of Mineralogy on Expansion Potential / 22
2.1.7 Effect of Type of Cation on Expansion Potential / 22

2.2 Macroscale Aspects of Expansive Soil Behavior / 24
2.2.1 Development of Natural Soil Deposits / 24
2.2.2 Effect of Plasticity on Expansion Potential / 26
2.2.3 Effect of Soil Structure, Water Content, and Density on Expansion Potential / 27
2.3 Identification of Expansive Soils / 30
2.3.1 Methods Based on Physical Properties / 30
2.3.1.1 Methods Based on Plasticity / 30
2.3.1.2 Free Swell Test / 31
2.3.1.3 Potential Volume Change (PVC) / 32
2.3.1.4 Expansion Index (EI) Test / 33
2.3.1.5 Coefficient of Linear Extensibility (COLE) / 35
2.3.1.6 Standard Absorption Moisture Content (SAMC) / 36
2.3.2 Mineralogical Methods / 36
2.3.3 Chemical Methods / 37
2.3.3.1 Cation Exchange Capacity (CEC) / 37
2.3.3.2 Specific Surface Area (SSA) / 38
2.3.3.3 Total Potassium (TP) / 39
2.3.4 Comments on Identification Methods / 39
2.4 Characteristics of Expansive Soil Profiles / 40
2.4.1 Geographic Distribution of Expansive Soils / 40
2.4.2 Expansive Soil Profiles / 40
2.4.2.1 Welkom, South Africa / 43
2.4.2.2 Maryland, Australia / 44
2.4.2.3 Regina, Saskatchewan, Canada / 44

2.4.2.4 Front Range Area of Colorado, USA / 46
2.4.2.5 San Antonio, Texas, USA / 52
References / 53

3. SITE INVESTIGATION / 59

3.1 Program of Exploration / 59
3.1.1 Reconnaissance Investigation / 60
3.1.2 Preliminary Investigation / 60
3.1.3 Design-Level Investigation / 61
3.1.3.1 Distribution of Borings / 62
3.1.3.2 Depth of Exploration / 64
3.1.3.3 Sampling Frequency and Depth / 65
3.2 Forensic Investigation / 68
References / 72

4. SOIL SUCTION / 74

4.1 Soil Suction Components / 74
4.1.1 Matric Suction / 76
4.1.2 Osmotic Suction / 80
4.1.3 Total Suction / 82
4.2 Soil Water Characteristic Curve / 82
4.2.1 Mathematical Expressions for SWCC / 84
4.2.2 Soil Water Characteristic Curves for Expansive Soils / 86
4.2.3 Influence of Stress State on Soil Water Characteristic Relationships / 89
4.2.4 Effect of Suction on Groundwater Profiles / 89
4.3 Measurement of Matric Suction / 90
4.3.1 Tensiometers / 92
4.3.2 Axis Translation Technique / 94
4.3.2.1 Pressure Plate Apparatus / 97
4.3.2.2 Fredlund SWCC Device / 97

4.3.3 Filter Paper Method for Matric Suction / 98
4.3.3.1 Principle of Measurement / 100
4.3.3.2 Calibration Curves / 101
4.3.3.3 Filter Paper Hysteresis / 102
4.3.3.4 Time Required to Reach Equilibrium / 102
4.3.4 Thermal Conductivity Sensors / 103
4.3.5 Electrical Resistance Sensors / 104
4.4 Measurement of Osmotic Suction / 105
4.4.1 Osmotic Tensiometers / 105
4.4.2 Pore Fluid Extraction Technique / 106
4.5 Measurement of Total Suction / 107
4.5.1 Psychrometers / 109
4.5.1.1 Thermocouple Psychrometers / 109
4.5.1.2 Chilled Mirror Psychrometer / 110
4.5.2 Filter Paper Method for Total Suction / 110
4.5.2.1 Principle of Measurement / 111
4.5.2.2 Calibration Curves / 111
4.5.2.3 Time Required to Reach Equilibrium / 112
References / 114

5. STATE OF STRESS AND CONSTITUTIVE RELATIONSHIPS / 119

5.1 State of Stress and Stress State Variables / 119
5.2 Stress–Volume Relationships / 124
5.3 Stress–Water Relationships / 125
References / 126

6. OEDOMETER TESTING / 127

6.1 Consolidation-Swell and Constant Volume Tests / 129
6.2 Correction of Oedometer Test Data / 132