

# FOUNDATION ENGINEERING FOR EXPANSIVE SOILS



JOHN D. NELSON | KUO CHIEH CHAO  
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# 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.

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# 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
$\Delta H$	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
$\Delta z$	thickness of soil layer
$\alpha$	compressibility factor
$\alpha$	soil to pier adhesion factor
$\alpha$	drainage slope
$\alpha_1$	coefficient of uplift between the pier and the soil
$\alpha_2$	coefficient of anchorage between the pier and the soil
$\beta$	contact angle with tube
$\beta$	reduction factor for expansive earth pressure
$\gamma$	unit weight of soil
$\gamma_d$	dry density of soil
$\gamma_{sat}$	saturated unit weight of soil
$\gamma_t$	total unit weight of soil
$\gamma_w$	unit weight of water
$\gamma_{\psi o}$	osmotic suction volumetric compression index
$\gamma_{\sigma}$	mean principal stress volumetric compression index
$\gamma_{\psi m}$	matric suction volumetric compression index
$\delta$	interface friction angle
$\delta_{max}$	differential heave
$\epsilon$	strain
$\epsilon_{iso}$	isotropic swelling strain
$\epsilon_s$	strain
$\epsilon_{sn}$	shrinking strain
$\epsilon_{sw}$	swelling strain
$\epsilon_T$	total range of strain
$\epsilon_{s\%}$	percent swell
$\epsilon_{s\%_0N}$	normalized percent swell
$\epsilon_{s\%_0VO}$	percent swell measured from a sample inundated at the overburden stress in the consolidation-swell test
$\theta$	volumetric water content
$\theta_f$	volumetric water content above the wetting front
$\theta_r$	residual volumetric water content
$\theta_s$	saturated volumetric water content
$\lambda$	pore size distribution index
$\nu$	number of ions from one molecule of salt
$\nu$	Poisson's ratio
$\rho$	heave



$\Delta\rho$	differential movement
$\rho_{\max}$	maximum heave
$\rho_0$	free-field heave
$\rho_p$	pier heave
$\rho_s$	solute mass/density
$\rho_{\text{ult}}$	total heave
$\sigma = (\sigma' + u_w)$	total stress, normal stress
$\sigma' = (\sigma - u_w)$	effective stress
$\sigma'' = (\sigma - u_a)$	net normal stress
$\sigma''_{\text{cs}}$	consolidation-swell swelling pressure
$\sigma''_{\text{cv}}$	constant volume swelling pressure
$\sigma''_{\text{cvN}}$	reduced swelling pressure
$\sigma_{\text{ext}}$	external stress
$\sigma''_{\text{f}}$	final vertical stress
$\sigma''_{\text{h}}$	lateral stress
$\sigma''_{\text{i}}$	inundation stress
$\sigma_{\text{int}}$	internal stress between particles
$\Delta\sigma''_{\text{v}}$	increment of applied stress
$\sigma_{\text{vo}}, \sigma'_{\text{vo}}, \sigma''_{\text{vo}}$	vertical overburden stress in terms of total, effective, or net normal stress
$\tau$	shear stress
$\phi$	osmotic coefficient
$\phi$	angle of internal friction
$\phi_p$	peak angle of internal friction
$\phi_r$	residual angle of internal friction
$\chi$	chi parameter
$\psi$	total suction
$\psi_{\text{ae}}$	air entry soil suction
$\psi_{\text{m}} = (u_a - u_w)$	matric suction
$\psi_{\text{o}}$	osmotic suction
$\psi_{\text{r}}$	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



# Introduction

The design of foundations for structures constructed on expansive soils is a major challenge for geotechnical engineers practicing in areas where such soils are prevalent. The forces exerted by expansive soils and the movements that they cause to even heavily loaded structures can be well in excess of those experienced by ordinary soils. Also, the costs associated with development of expansive soil sites are much higher than those for nonexpansive soil sites. The site investigation and design phase requires more extensive testing and analyses, and the construction phase requires more inspection and attention to detail. Special considerations must be addressed during their occupancy with regard to the maintenance of facilities constructed on expansive soils. Furthermore, the cost to repair the problems caused by expansive soils may be prohibitive. There are many examples where repair costs exceed the original cost of construction.

The nature of expansive soils and the magnitude of costs associated with shortcomings in design, construction, and operation are such that there exists little margin for error in any phase of a project. In that regard, the following quote is appropriate (Krazynski 1979):

To come even remotely close to a satisfactory situation, trained and experienced professional geotechnical engineers must be retained to evaluate soil conditions. The simple truth is that it costs more to build on expansive soils and part of the cost is for the professional skill and judgment needed. Experience also clearly indicates that the cost of repairs is very much higher than the cost of a proper initial design, and the results are much less satisfactory.

In the initial phases of a project, the owner or developer is faced with costs that may be significantly higher than initially estimated. They generally are intolerant of shortcomings and demand that the foundations be designed and constructed such that the movements are within tolerable limits. At the same time, they are reluctant to undertake the required additional cost for something that exists below ground and

cannot be seen. One large foundation contractor, Hayward Baker, has as part of its motto, “You never see our best work.” An important task of the engineer is to convince the client that the additional cost is not merely justified, but is critical. This is especially true for critical structures such as hospitals and public buildings, where failure could have serious consequences.

Expansive soils problems exist on every continent, with the exception perhaps of Antarctica. Expansive soils have been encountered in almost every state and province of the United States and Canada, but they are more troublesome in the western and southwestern areas because areas of low precipitation often tend to be more problematic.

In spite of the fact that expansive soils have been designated a geologic hazard, public awareness is lacking. Few universities offer formal courses relating to geotechnical applications for expansive soils. There is a shortage of continuing education courses in the subject, and research is limited to a relatively small number of institutions. As a result, few practicing foundation engineers have received formal education in this area. It is intended that this book will provide a service for awareness, education, and technical reference in this important area.

### **1.1 PURPOSE**

This book is intended to provide the background and principles necessary for the design of foundations for expansive soils. The nature of expansive soil is described from an engineering perspective to develop an appreciation as to how the microscopic and macroscopic aspects of soil interact to affect expansive behavior. Tools that are necessary to use in the practice of expansive soil foundation design are developed in a fashion that can be easily implemented. The application of these tools to the design of foundations is demonstrated.

An important underlying theme of the book is the ability to predict ground heave and structural movement caused by expansive soil. This is a fundamental part of foundation design. Rigorous calculations of slab heave and potential movement of deep foundations should be a part of every design. Several chapters in this book are devoted to that important subject.

### **1.2 ORGANIZATION**

The organization of this book is designed to first present the fundamental nature of expansive soil and then address the factors that influence expansion. Those tools provide the means for the design of foundations