Fourth Edition

Fundamentals of Soil Behavior

James K. Mitchell

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WILEY

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

Library of Congress Cataloging-in-Publication Data Applied for:

Hardback ISBN: 9781119832317

Cover Design: Wiley

Set in 10.5/12pt Times by Straive, Pondicherry, India

DEDICATION - JAMES K. MITCHELL

While we are pleased that the fourth edition of this book is being published, we are sad that James (Jim) K. Mitchell, the first author of this book, was not able to see the completion of this endeavor. Jim passed away peacefully at his home in Massachusetts on December 17, 2023. We dedicate this fourth edition to his memory.

Jim was born in Manchester, New Hampshire, on April 19, 1930. He earned a Bachelor of Science degree from Rensselaer Polytechnic Institute in 1951, a Master of Science degree from the Massachusetts Institute of Technology (MIT) in 1953, and a Doctor of Science from MIT in 1956. After completing his studies at MIT, he worked for a year as a soil engineer at the US Army Engineer Waterways Experiment Station (now part of the US Army Engineering Research and Development Center) in Vicksburg, Mississippi. Subsequently, he spent 1956–1958 as an officer in the US Army Corps of Engineers, stationed in the United States and Germany.

In 1958, Jim joined the Civil Engineering faculty at University of California Berkeley (UC Berkeley) as assistant professor. Together with his senior Berkeley colleagues, he was instrumental in developing a world-class teaching and research program in geotechnical and geoenvironmental engineering. He was a consummate teacher and researcher, creating the first civil engineering course nationally that applied the sciences of soil mineralogy and chemistry to explain fundamental aspects of the engineering behavior of soil. He retired from UC Berkeley in 1993 and joined the faculty at Virginia Polytechnic Institute and State University (Virginia Tech) in 1994. He retired from Virginia Tech in 1999. While officially retired, Jim continued to be very active in guiding research, co-teaching courses, authoring papers, and contributing in other ways to the profession. He worked co-writing this edition until near the time of his death.

Throughout his career, Jim made significant contributions in the field of soil behavior and soil property evaluation. During his doctoral research at MIT, he conducted pioneering studies on the fabric of compacted clay. Additionally, he conducted early research at UC Berkeley on compacted clay, soil stabilization, and time-dependent aspects of soil behavior. Over the first two decades of his academic career, he provided a framework for considering soil behavior from micro-scale mineralogical and chemical principles to macro-scale engineering properties.

During the Apollo Missions 14 to 17 from 1969 to 1972, as the Principal Investigator for the NASA Apollo Lunar Soil Mechanics Experiment, he was responsible for designing, executing, and evaluating mission planning, astronaut activities on the moon's surface, and post-mission analyses. These efforts provided a comprehensive understanding of the properties and engineering behavior of lunar soil. This knowledge serves as a basis for improved scientific understanding and engineering applications as space exploration and development have now resumed.

After the 1989 Loma Prieta Earthquake in California, Jim conducted a study for the Mayor of San Francisco to investigate the reasons for the significant earthquake damage in the Marina District. He also provided recommendations on measures that property owners and the city could take to minimize future earthquake losses. Over the course of the next 20 years, Jim made a number of valuable contributions to the field of geotechnical earthquake engineering.

In his career, Jim worked as a consultant on significant engineering projects, many of which involved ground stabilization, ground improvement, and the rehabilitation and retrofit of existing dams and other infrastructure, especially for seismic safety. He has been recognized with numerous awards and honors, including his elections to the National Academy of Engineering (NAE, 1976) and the National Academy of Sciences (NAS, 1998). Moreover, he has received multiple awards from the American Society of Civil Engineers, such as the Middlebrooks Award four times, the Norman Medal twice, the H. Bolton Seed Medal (2004), and the OPAL Lifetime Achievement Award in Education (2006). He was also named a distinguished member of ASCE in 1993. Furthermore, he delivered notable lectures including the ASCE Terzaghi Lecture in 1984 and the British Geotechnical Society Rankine Lecture in 1991.

Jim was an exceptional friend and mentor to many of his colleagues and students. Despite his numerous accomplishments, he remained humble and always willing to learn something new. He was a role model to his students and always generous with his time. Jim was always willing to help his colleagues and students, often extending this help throughout their careers. He loved the outdoors and music and was an accomplished saxophone player, an avocation that he enjoyed throughout his life.

Jim is survived by his wife of 16 years, Holly Taylor, and by five children and their families. Jim and his late wife, Virginia "Bunny" Mitchell, raised their family while Jim was a professor at UC Berkeley. He is also survived by nine grandchildren and was a later-life father and grandfather to Holly's two daughters and grandson.

While Jim was not with us for the final stages of bringing the process of revising the book to completion, he actively and enthusiastically drove the project from January 2021 until December 2023, via weekly video calls across three time zones. He had read and commented on drafts of all 13 chapters that were close to the final published versions. It was an absolute privilege to work on this fourth edition with Jim.

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August 2024

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PREFACE

The National Research Council (1989, 2006), its committee on Geological and Geotechnical Engineering (COGGE), and Lu and Mitchell (2019) have identified the role of geoengineering in addressing critical societal needs. These include, but are not limited to, (i) climate change mitigation and adaptation; (ii) waste management and environmental protection; (iii) energy and water resource identification, recovery, and storage; (iv) infrastructure development, rehabilitation, security, sustainability, and resilience; (v) construction efficiency and innovation; (vi) resource discovery and recovery; (vii) mitigation of natural hazards; and (viii) the exploration and development of new frontiers.

Solving problems and completing projects in these areas require a solid understanding of the composition, structure, and behavior of soils, as virtually all structures and facilities are built on, in, or with the Earth. The purpose of this book remains the same as for the prior three editions: to develop an understanding of the factors determining and controlling the engineering properties and behavior of soils under different conditions, with an emphasis on ***why*** they are ***what*** they are. We believe that this understanding and its prudent application are valuable assets in meeting these societal needs.

The format of the book has stayed mostly the same as in the first three editions. However, we have thoroughly reviewed and revised the contents, removing some material that is no longer essential and adding substantial new material to integrate recent important developments. We have also reorganized the material among chapters to improve the flow of topics and the logic of presentation. Additionally, we have separated thermal effects on soil strength and deformation behavior into a new chapter.

For this fourth edition, we are indebted to innumerable students and professional colleagues in the form of valuable comments, figures, photos, resources, and proof checking, which were made by Susan Burns, Bodhinanda Chandra, Wonjun Cha, Kecheng Chen, Sihua Chen, Jason DeJong, Chuao Dong, Connor Geudeker, Joana Fonseca, Joel Given, Gyubeom Shin, Shaivan Hirebelaguly Shivaprakash, Xin Huang, Tadahiro Kishida, Maksymilian Jasiak, Deyun Liu, Masahide Otsubo, Tokio Morimoto, Yohei Nakamichi, Vincenzo Nardelli, Aine Ní Bhreasail, Jose Salomon, David Taborda, Lauren Talbot, Howard Taylor, Tianchen Xu, and Yaobin Yang.

JKM thanks his wife, Holly, for her support and encouragement.
KS thanks his wife, Mikiko, and daughter, Minami, for their encouragement and special support.
COS thanks her husband, John, and son, Oisín, for their patience and support.

LIST OF SYMBOLS

a area
a coefficient for harmonics
a cross-sectional area of a tube
a crystallographic axis direction or distance
a effective cluster contact area
a volumetric air content
a thermal diffusivity
a_c effective area of interparticle contact
a_m coefficient of compressibility with respect to changes in water content
a_t coefficient of compressibility with respect to changes in $(\sigma - u_a)$
a_v coefficient of compressibility in one dimensional compression
A activity
A area
A creep rate parameter
A cross section area normal to the direction of flow
A Hamaker constant
A long-range interparticle attractions
A Skempton's pore pressure parameter
A thermal diffusivity
A van der Waal's constant
A' short-range attractive stress
$\overline{A}$ pore pressure parameter = $\Delta u/\Delta(\sigma_1 - \sigma_3)$
A_0 concentration of charges on pore wall
A_0 surface charge density per unit pore volume
A_c solid contact area
A_f area of flow passages
$\overline{A}_f$ pore pressure parameter at failure
A_h Hamaker constant
A_i state parameter in disturbed state
A_i total surface area of the ith grain
A_i^0 state parameter at equilibrium
A_s specific surface area per unit weight of solids
Å Angstrom unit = 1×10^{-10} m
b coefficient of harmonics
b crystallographic axis direction or distance
b intermediate stress parameter
B parameter in rate process equation = $X(kT/h)$
B Bishop's pore water pressure coefficient
B_q grain breakage parameter
B_r Hardin's relative breakage parameter
c cohesion
c cohesion intercept in total stress
c concentration
c molar concentration
c crystallographic axis direction or distance
c undrained shear strength
c velocity of light
c' cohesion intercept in effective stress
c_0 equilibrium solution concentration, bulk solution concentration
c_0^+ cation equilibrium solution concentration
c_0^- anion equilibrium solution concentration
c_a mid-plane anion concentration
c_e, c'_e Hvorslev's cohesion parameter
cec cation exchange capacity
c_{ic}, c_c mid-plane cation concentration
c_{i0} equilibrium solution concentration
c_m mid-plane concentration
c'_m mid-plane anion concentration
c_u undrained shear strength
c_v coefficient of consolidation
c_w concentration of water
C capacitance
C chemical concentration
C clay content by weight
C composition
C electrical capacitance
C short-range repulsive force between contacting particles
C soil compressibility
C speed of light in vacuum or in air, 3×10^8 m/sec
C volumetric heat
C volumetric heat capacity
C_c compression index
C_c^* intrinsic compression index
C_l compressibility of pore fluid
C_n coordination number

CR	compression ratio
CRR	cyclic resistance ratio
C_s	compressibility of a solid
C_s	shape coefficient
C_s	swelling index
C_u	coefficient of uniformity
C_u	compressibility of soil skeleton by pore pressure change
C_W	compressibility of water
C_α, $C_{\alpha e}$	coefficient of secondary compression
d	diameter
d	distance
d_{10}	sieve size that 10% of the particles by weight pass through
d_{60}	sieve size that 60% of the particles by weight pass through
dx	incremental horizontal displacement at peak
dy	incremental vertical displacement at peak
D	diameter of particle
D	dielectric constant, relative permittivity
D	diffusion coefficient
D	deviator stress
$\overline{D}$	stress level = $D/D_{\max}$
D_0	molecular diffusivity of water vapor in air
D_0	self-diffusion coefficient
D_{50}	sieve size that 50% of the particles by weight pass through
D_{eff}	effective diameter
D_{eV}	isothermal vapor diffusivity
D_{max}	strength at the beginning of creep
D_R, D_r	relative density
D_s	characteristic grain size
D_{TV}	thermal vapor diffusivity
D^*	effective diffusion coefficient
e	electronic charge = 4.8029×10^{-10} esu = 1.60206×10^{-10} coulomb
e	void ratio
e_0	initial void ratio
e^*_{100}	intrinsic void ratio under effective vertical stress of 100 kPa
e_c	intracluster void ratio
e_{cs}	void ratio at critical state
e_{ff}	void ratio at failure
e_g, e_G	void ratio of the granular phase, granular void ratio
e_{ini}	initial void ratio
e_L	void ratio at liquid limit
e_{max}	maximum void ratio
e_{min}	minimum void ratio
e_p	intercluster void ratio
e_T	total void ratio
E	experimental activation energy
E	potential energy
E	Young's modulus
E	voltage, electrical potential
E_{50}	secant modulus at 50 percent of peak strength
E_{max}	small strain Young's modulus
$\overline{E}_r$	rebound modulus
ESP	exchangeable sodium percentage
$E(\beta)$	distribution function for interparticle contact plane normals
f	force acting on a flow unit
f	frequency
f_i	fraction of particles between two sizes
f^n	normal force
f^t	tangential force
F	force of electrostatic attraction
F	formation factor
F	free energy
F	freezing index
F	pressure-temperature parameter
F	tensile strength
F, F_0	Faraday constant = 96,500 coulombs
$\overline{F}$	partial molar free energy on adsorption
F_d	free energy of the double layer per unit area at a plate spacing of $2d$
ΔF	free energy of activation
F_E	electrical force per unit length
F_H	hydraulic seepage force per unit length causing flow
FI	fabric index
F_∞	free energy of a single non-interacting double layer
g	acceleration due to gravity
G	shear modulus
G	source-sink
G_{1000}	shear modulus measured after 1000 minutes of constant confining pressure
G_g	shear modulus of grains
G_{max}	small strain shear modulus
G_s	secant shear modulus
G_s	specific gravity of soil solids
G_{SC}	specific gravity of clay particles
G_{SG}	specific gravity of the granular particles
h	head or head loss
h	relative humidity of air in pores
h	Planck's constant = 6.624×10^{-27} erg sec
h_m	matrix or capillary head
h_s	osmotic or solute head
H	maximum distance to drainage boundary
H	stress history
H	thickness
H	total head
H	water transport by ion hydration
$\overline{H}$	partial molar heat content
i	gradient

i	unit vector
i_c	chemical gradient
i_e	electrical gradient
i_h	hydraulic gradient
i_t	thermal gradient
I	electrical current
I	intensity
I_1, I_2, I_3	stress invariants
I_G	coefficient of shear modulus increase with time
I_R	dilatancy index
I_v	void index
J_c	chemical flow rate
J_D	chemical flow rate
J_i	flux of constituent i
J_i	value of property i in clay-water system
J_s	flow rate of salt relative to fixed soil layer
J_v	volume flow rate of solution
J_w	flow rate of water
J_i^0	value of property i in pure water
k	Boltzmann's constant = 1.38045×10^{-23} J/°K
k	hydraulic conductivity, hydraulic permeability
k	mean coordination number of a grain
k	selectivity coefficient
k	thermal conductivity
k	true cohesion in a solid
k_0	pore shape factor
k_c	osmotic conductivity
k_e	electro-osmotic conductivity
k_h	hydraulic conductivity
k_i	constant characteristic of a property
k_r	relative permeability
k_s	saturated conductivity
$k(S)$	saturation dependent hydraulic conductivity
k_t	thermal conductivity
k_θ	unsaturated hydraulic conductivity
K	absolute permeability or intrinsic permeability
K	bulk modulus
K	double-layer parameter = $(8\pi n_0 e^2 v^2/DRT)^{1/2}$
K	pore shape factor
K	rate of increase in tip resistance in logarithmic time
K_0	coefficient of lateral earth pressure at rest
K_a	coefficient of active earth pressure
K_c	principal stress ratio
K_c	principal stress ratio during consolidation
K_d	distribution coefficient
K_p	coefficient of passive earth pressure
K_{so}	stress-optical material constant
K_α	wavelengths of monochromatic radiation
l	length
l	material thickness
l	total number of pore classes

L	latent heat of fusion
L	length
L_{ij}	coupling coefficient or conductivity coefficient
LI	liquidity index
LI_{eq}	equivalent liquidity index
LL	liquid limit
L_s	latent heat of fusion of water
m	slope of relationship between log creep strain rate and log time
m	total mass per unit total volume
m	total number of pore classes
m_c	mass of clay
m_s	compressibility of mineral solids under hydrostatic pressure
m_s'	compressibility of mineral solids under concentrated loadings
m_v	compressibility
m_w	compressibility of water
m_w	mass of water
M	constrained modulus or coefficient of volume change
M	metal cations
M	monovalent cation concentration
n	concentration, ions per unit volume
n	harmonic number
n	integer
n	number of grains in an ideal breakage plane
n	porosity
n	total number of pore classes
n	unspecified atomic ratio
n_0	concentration in external solution
n_1	number of bonds per unit of normal force
n_e	effective porosity
n_i	Refractive index in i direction
N	Avogadro's number = 6.0232×10^{23} mole^{-1}
N	coordination number
N	monovalent cation concentration
N	normal load or force
N	number of moles of hydration water per mole of ion
N	number of particles per cluster in a cluster structure
N	number of weeks since disturbance
N	total number of harmonics
N_1	number of load cycles to cause liquefaction
N_e	number of load cycles
N_G	normalized shear modulus increase with time
N_s	moles of water per unit volume of sediment
N_w	moles of salt per unit volume of sediment
OCR	overconsolidation ratio
p	constant that accounts for the interaction of pores of various sizes
p	hydrostatic pressure

p	matrix or osmotic pressure
p	pressure
p	partial pressure of water vapor in pore space
p	vertical consolidation pressure
p'	mean effective pressure
p_o	present overburden pressure
p_a	atmospheric pressure
p_c	preconsolidation pressure
p'_{cs}	mean effective pressure at critical state
p_s	osmotic or solute pressure
p_z	gravitational pressure
P	area
P	bond strength per contact zone
P	concentration of divalent cations
P	power consumption
P	total gas pressure in pore space
P	total pressure
P	wetted perimeter
P_c	capillary pressure
$\hat{P}_c$	capillary pressure at air entry
P_f	injection pressure that causes clay to fracture
PI	plasticity index
P_{inj}	injection pressure
PL	plastic limit
P_N	probability distribution of normal contact force
PR	peak ratio
P_s	swelling pressure
P_T	probability distribution of tangential contact force
q	degree of connectivity between water-conducting pores
q	deviator stress
q	flow rate
q	hydraulic flow rate
q_c	CPT tip resistance
q_{cs}	deviator stress at critical state
q_f	deviator stress at failure
q_h	hydraulic flow rate
q_{hc}	osmotic flow rate
q_{he}	electro-osmotic flow rate
q_i	concentration of solids
q_t	heat flow rate
q_{vap}	vapor flux density
q_w	water flow rate
Q	electrical charge
Q	quantity of heat
r	pore radius
r	radius
r_k	ratio of horizontal to vertical hydraulic conductivities
r_p	pore size
r_p	tube radius
R	coefficient of roundness
R	electrical resistance
R	gas constant = 1.98726 cal/°K-mole 8.31470 joules/°K-mole 82.0597 cm^3 atm/°K-mole
R	long-range repulsion pressure
R	ratio of cations and anions
R	source or sink mass transfer term
R	sphere radius
R	tube radius
R_d	retardation factor
R_H	hydraulic radius
R_p	average particle radius
$R(\theta)$	radius at angle θ
s	slope of stress relaxation curve
s_u	undrained shear strength
S	entropy
S	fraction of molecules striking a surface that stick to it
S	number of flow units per unit area
S	partial molar entropy
S	saturation
S	specific surface area per unit volume of solids
S	structure
S	swell
$\overline{S}$	partial molar entropy
S_0	specific surface per unit volume of soil particles
SAR	sodium adsorption ratio
S_t	sensitivity
S_u	undrained shear strength
S_w	water saturation ratio
S_x, S_y, S_z	projected areas of interparticle contact surfaces
t	average thickness
t	tetrahedral coordinations
t	time
t	transport number
t_1	reference time
t_f	time to failure
t_m	time for adsorption of a monolayer
T	intercluster tortuosity
T	shear force
T	temperature
T	time factor
T_0	initial temperature
T_c	intracluster tortuosity
T_c	temperature at consolidation
T_{FP}	freezing temperature
T_s	surface temperature
T_s	temperature of shear for consolidated undrained direct shear tests
T_V	time factor
u	excess pore pressure
u	ionic mobility
u	midplane potential function

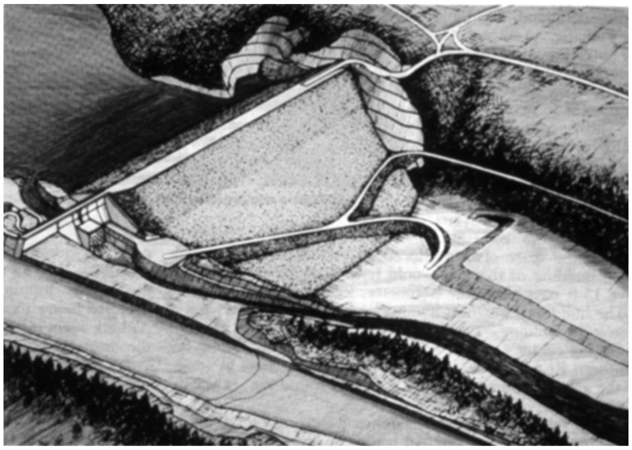
u	pore water pressure
u	pore water pressure in the interparticle zone
u	pressure
u	thermal energy
u^*	effective ionic mobility
u_0	initial pore pressure
u_0	pore water pressure remote from the interparticle zone
U_f	pore pressure at failure
U	average degree of consolidation
v	flow velocity
v	frequency of activation
v	ionic valance
v	settling velocity
v	specific volume = 1 + e
v_{ave}	average flow velocity
v_c^0	specific volume of the pure clay
v_{cs}	specific volume at critical state
v_h	apparent water flow velocity
V	area
V	difference in self-potentials
V	electrical potential
V	speed
V	valence
V	voltage
V	volume
V_0	initial volume
V_A	attractive energy
V_{DR}	volume of water drained
V_{GS}	volume of granular solids
V_m	total volume of soil mass
V_p	compression wave velocity
V_R	repulsive energy
V_s	shear wave velocity
V_s	volume of solids
V_w	partial molar volume of water
V_w	volume of water
w	water content
w_L, w_l	liquid limit
w_P, w_p	plastic limit
W	water content
W	width
W	fluid volume
W	water transport
W	weight
x	distance from the clay surface
X	distance
X	friction coefficient
X_i	driving force
y	potential function = $ve\Psi/kT$
z	direction of gravity
z	distance from drainage surface
z	electrolyte
z	ionic valence
Z	elevation or elevation head
Z	number of molecules per second striking a surface
Z	potential function = $ve\psi_0/kT$
α	angle between b and c crystallographic axes
α	directional parameter
α	disturbance factor
α	geometrical packing parameter
α	inclination of failure plane to horizontal plane
α	slope of the relationship between logarithm of creep rate and creep stress
α	thermal ratio
α	tortuosity factor
α_G	normalized strain rate parameter
α_s	thermal expansion coefficient of soil solids
α_{ST}	thermal expansion coefficient of soil structure
α_w	thermal expansion coefficient of water
β	angle between a and c crystallographic axes
β	birefringence ratio
β	disturbance factor
β	geometrical packing parameter
β	rotation angle of yield envelope
β_0, β_i	constant characteristic of the property and the clay
χ	Bishop's unsaturated effective stress parameter
δ	clay plate thickness measured between centers of surface layer atoms
δ	deformation parameter in Hertz theory
δ	displacement, distance
δ	solid fraction of a contact area
δ	relative retardation
δ_p	particle eccentricity distance
ε	dielectric constant, permittivity
ε	porosity
ε	strain
$\dot{\varepsilon}$	strain rate
ε_0	permittivity of vacuum, 8.85×10^{-12} $C^2/(Nm^2)$
ε_1	axial strain
$\dot{\varepsilon}_a$	vertical strain rate in one dimensional consolidation
ε_f	strain at failure
$\dot{\varepsilon}_{\min}$	minimum strain rate
ε_{rd}	volumetric strain that would occur if drainage were permitted
ε_s	deviator strain
$\dot{\varepsilon}_s$	deviator strain rate
ε_v	volumetric strain
$\dot{\varepsilon}_v$	volumetric strain rate
ΔE	energy dissipated per cycle per unit volume
ϕ	friction angle
ϕ	local electrical potential
ϕ'	friction angle in effective stress
ϕ^b	angle defining the rate of increase in shear strength with respect to soil suction
ϕ_c	characteristic friction angle

ϕ'_{crit} friction angle at critical state
ϕ_e, ϕ'_e Hvorslev friction parameter
ϕ'_f friction angle corrected for the work of dilation
ϕ'_m peak mobilized friction angle
ϕ'_r residual friction angle
ϕ_{repose} angle of repose
ϕ_v apparent specific volume of the water in a clay/water system of volume V
ϕ_μ, ϕ'_μ intergrain sliding friction angle
Φ dissipation function
γ activity coefficient
γ angle between a and b crystallographic axes
γ unit weight
$\dot{\gamma}$ shear strain rate
γ_c applied shear strain or cyclic shear strain amplitude
c_d dry unit weight
Γ double layer charge
Γ specific volume intercept at unit pressure
η dynamic viscosity
η fraction of pore pressure that gives effective stress
η_0 initial anisotropy
κ swelling index
κ' real relative permittivity
κ'' polarization loss, imaginary relative permittivity
λ compression index
λ correction coefficient for frost depth prediction equation
λ damping ratio
λ decay constant
λ pore size distribution index
λ separation distance between successive positions in a structure
λ wave length of X ray
λ wave length of light
λ_{cs} critical state compression index
μ chemical potential
μ coefficient of friction
μ dipole moment
μ fusion parameter
μ Poisson's ratio
μ viscosity
M critical state stress ratio
ν Poisson's ratio
ν_b Poisson's ratio of soil skeleton
π osmotic or swelling pressure
θ angle of bedding plane relative to the maximum principal stress direction
θ contact angle
θ geometrical packing parameter
θ liquid-to-solid contact angle
θ orientation angle
θ volumetric water content
θ_m volumetric water content at full saturation
θ_r residual water content
θ_s volumetric water content at full saturation
ρ bulk dry density
ρ charge density
ρ mass density
ρ_d bulk dry density
ρ_T resistivity of saturated soil
ρ_w density of water
ρ_W resistivity of soil water
σ area occupied per absorbed molecule on a surface
σ double-layer charge
σ electrical conductivity
σ entropy production
σ normal stress
σ surface tension of water
σ surface charge density
σ total stress
σ' effective stress
σ'_0 initial effective confining pressure
σ_1 major principal total stress
σ_1 tensile strength of the interface bond
σ'_1 major principal effective stress
σ_{1c} major principal stress during consolidation
σ_{1f} major principal stress at failure
σ'_{1ff} major principal effective stress at failure
σ'_2 intermediate principal effective stress
σ_3 minor principal total stress
σ'_3 minor principal effective stress
σ_{3c} minor principal stress during consolidation
σ'_{3ff} minor principal effective stress at failure
σ'_a axial effective stress
σ'_{ac} axial consolidation stress
σ_{as} interfacial tension between air and solid
σ_{aw} interfacial tension between air and water
σ_c crushing strength of particles
σ_c tensile strength of cement
σ_e electrical conductivity
σ'_e equivalent consolidation pressure
σ_{eff} effective AC conductivity
σ_f partial stress increment for fluid phase
σ'_f effective normal stress on shear plane
σ_{ff} normal total stress on failure plane
σ'_{ff} normal effective stress on failure plane
σ_h electrical conductivity due to hydraulic flow
σ'_{h0} initial horizontal effective stress
σ'_i effective stress in the i-direction
σ'_i intergranular stress
σ'_i isotropic consolidation
σ_{iso} isotropic total stress
σ_{max} maximum principal stress
σ_{min} minimum principal stress

σ'_n	effective normal stress
σ'_p	preconsolidation pressure
σ_r	radial total stress
σ'_r	radial effective stress
σ'_{rc}	radial consolidation stress
σ_s	conductivity of soil surface
σ_s	partial stress increment for solid phase
σ_s	tensile strength of the sphere
σ_T	electrical conductivity of saturated soil
σ_T, σ'_t	tensile strength of cemented soil
σ_v	vertical stress
σ'_v	vertical effective stress
$\overline{\sigma}_{v0}$	overburden vertical effective stress
σ'_{v0}	overburden effective stress
σ'_{vm}	maximum past overburden effective stress
σ'_{vp}	vertical preconsolidation stress
σ_W	electrical conductivity of pore water
σ_{ws}	interfacial tension between water and solid
σ_y	yield strength
σ_θ	circumferential stress
τ	shear strength
τ	shear stress
τ	surface tension
τ	swelling pressure or matric suction
τ	undrained shear strength
τ_a	apparent tortuosity factor
τ_c	applied shear stress
τ_c	contaminant film strength
τ_{cy}	undrained cyclic shear stress
τ_d	drained shear strength
τ_{ff}	shear stress at failure on failure plane
τ_i	shear strength
τ_i	shear strength of contact
τ_m	shear strength of solid material in yielded zone
τ_{peak}	applied shear stress at peak
τ_α	initial static shear stress
ν	mass flow factor
ν	cation valence
ξ	distance function = Kx, double-layer theory
ξ	ratio of average temperature gradient in air filled pores to overall temperature gradient
ψ	dilation angle
ψ	electrical potential
ψ	intrinsic friction angle
ψ	matric suction
ψ_0	surface potential of double layer
ψ_d	displacement pressure
Ψ	electrical potential
Ψ	state parameter
Ψ	total potential of soil water
Ψ_0	electrical potential at the surface
Ψ_s	gravitational potential
Ψ_m	matrix or capillary potential
Ψ_p	gas pressure potential
Ψ_s	osmotic or solute potential
ω	angular velocity
ω	frequency
ω	osmotic efficiency
Ω	true electroosmotic flow
ζ	zeta potential

CHAPTER 1

Introduction



Successful design, construction, and long-term performance of a complex earth embankment dam such as this requires knowledge and understanding of all four dimensions of soil behavior—volume change properties, stress and deformation characteristics, flow of fluid through the materials, and changes in these properties with time.

1.1 SOIL BEHAVIOR IN CIVIL AND ENVIRONMENTAL ENGINEERING

Civil and environmental engineering includes the conception, analysis, design, construction, operation, and maintenance of a diversity of structures, facilities, and systems. All are built on, in, or with soil or rock. The long-term properties and behavior of these materials have major influences on the success, economy, sustainability, resilience, and safety of the work. Geoengineers play a vital role in these projects and are also concerned with virtually all aspects of environmental control, including water resources, water pollution control, waste disposal and containment, and the mitigation of such natural disasters as floods, earthquakes, landslides, and volcanoes. Furthermore, detailed understanding of the behavior of earth materials is essential for mining, for energy resources development and recovery, and for scientific studies in virtually all the geosciences.

To deal properly with the earth materials associated with any of these problems and projects requires knowledge, understanding, and appreciation of the importance of geology, materials science, materials testing, and mechanics. Geotechnical engineering is concerned with all of these. Environmental concerns—especially those related to groundwater, the safe disposal and containment of wastes, and the cleanup of contaminated sites—have spawned yet another area of specialization; namely, environmental geotechnics, wherein chemistry and biological science are important. The impacts of geochemical and microbiological phenomena on the composition, properties, and stability of soils and rocks are now known to be significant.

Students in civil engineering are often quite surprised, and sometimes quite confused, by their first course in engineering with soil. After studying statics, mechanics, and structural analysis and design, wherein problems are usually quite clear-cut and well defined, they are suddenly confronted with situations where this is no longer the case. A first course in soil mechanics may not, at least for the first half to two-thirds of the course, be mechanics at all. The reason for this is simple: analyses and designs are useless if the boundary conditions and material properties are improperly defined.

Acquisition of the data needed for analysis and design on, in, and with soils and rocks can be far more difficult and uncertain than when dealing with other engineering materials. There are at least three reasons for this.

1. *No Clearly Defined Boundaries:* An embankment resting on a soil foundation is shown in Fig. 1.1*a*, and a cantilever beam fixed at one end is shown in Fig. 1.1*b*. The free body of the cantilever beam, Fig. 1.1*c*, is readily analyzed for reactions, shears, moments, and deflections using standard methods of structural analysis. However, what are the boundary conditions, and what is the free body for the embankment foundation?
2. *Variable and Sometimes Unknown Material Properties:* The properties of most construction materials (e.g., steel, plastics, concrete, aluminum, and wood) are ordinarily known within rather narrow limits and usually can be specified to meet certain needs. Although this may be the case in

Fundamentals of Soil Behavior, Fourth Edition. James K. Mitchell, Kenichi Soga, and Catherine O'Sullivan.

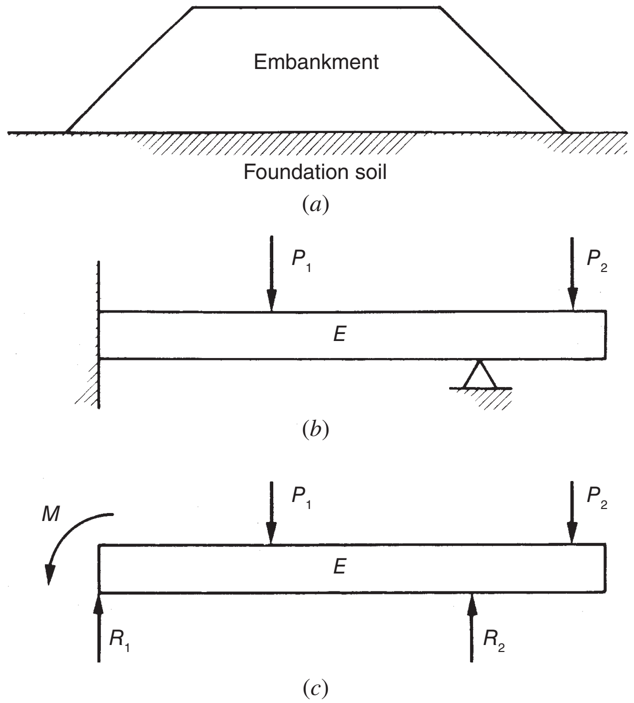


Figure 1.1 The problem of boundary conditions in geotechnical problems: (*a*) embankment on soil foundation, (*b*) propped cantilever beam, and (*c*) free body diagram for its analysis.

construction using earth and rock fills, at least part of every geotechnical problem involves interactions with in situ soil and rock. No matter how extensive and expensive any boring and sampling program is, only a very small percentage of the subsurface material is available for observation and testing. In most cases, more than one stratum is present, and conditions are nonhomogeneous and anisotropic.

3. *Stress and Time-Dependent Material Properties:* Soils and some rocks have mechanical properties that depend on both the stress history and the present stress state. This is because the volume change, stress–strain, and strength properties depend on stress transmission between particles and particle groups. These stresses are mostly generated by body forces and boundary stresses and not by internal forces of cohesion, as is the case for many other materials. In addition, the properties of most soils change with time after placement, exposure, and loading. Because of these stress and time dependencies, any given geotechnical problem may involve not just one or two but an almost infinite number of different materials.

Adding to the above three factors the fact that soil and rock properties may be susceptible to influences from changes in temperature, pressure, water availability, and chemical and biological environment, one might conclude that successful application of mechanics to earth materials is an almost hopeless proposition. It has been amply demonstrated, of course, that this is not the case; in fact, it is for these very reasons that geotechnical engineering offers such a great challenge for imaginative and creative work.

Modern theories of soil mechanics, the capabilities of modern computers and numerical analysis methods, and our improved knowledge of soil physics and chemistry make possible the solution of a great diversity of static and dynamic problems of stress deformation and stability, the transient and steady-state flow of fluids through the ground, and the long-term performance of earth systems. Nonetheless, our ability to analyze and compute often exceeds our ability to understand, measure, and characterize a problem or process. Thus, understanding and the ability to conceptualize soil and rock behavior become more important.

The objectives of this book are to provide a basis for the understanding of the engineering properties and behavior of soils and the factors controlling changes with time, and to indicate why this knowledge is important and how it can be used in the solution of geotechnical and geoenvironmental engineering problems.

It is easier to state what this book is not, rather than what it is. It is not a book on soil or rock mechanics; it is not a book on soil exploration or testing; it is not a book that teaches analysis or design; and it is not a book on geotechnical engineering practice. Excellent books and references dealing with each of these important areas are available.

It is a book on the composition, structure, and behavior of soils as engineering materials. It is intended for students, researchers, and practicing engineers who seek a more in-depth knowledge of the nature and behavior of soils than is provided by classical and conventional treatments of soil mechanics and geotechnical engineering.

Here are some examples of the types of questions that are addressed in this book:

- What are soils composed of? Why? How did they get the way they are?
- How does geological history influence soil properties?
- How are engineering properties and behavior related to composition?
- What is clay?
- Why are clays plastic?
- What are friction and cohesion?

- What is *effective* stress? Why is it important?
- Why does soil creep and exhibit stress relaxation?
- Why do some soils swell while others do not?
- Why does stability failure sometimes occur at stresses less than the measured strength?
- Why and how are soil properties changed by disturbance?
- How do changes in environmental conditions change soil properties?
- What are some practical consequences of the prolonged exposure of clay containment barriers to waste chemicals?
- What controls the rate of flow of water, heat, chemicals, and electricity through soil?
- How are the different types of flows through soil interrelated?
- Why is the residual strength of soil often much less than its peak strength?
- How do soil properties change with time after deposition or densification and why?
- How do temperature changes influence the mechanical properties of soils?
- What is soil liquefaction, and why is it important?
- What causes frost heave, and how can it be prevented?
- What clay types are best suited for sealing waste repositories?
- What biological processes can occur in soils and why are they important in engineering problems?

Developing answers to questions such as these requires the application of concepts from chemistry, geology, biology, materials science, and physics. Principles from these disciplines are introduced as necessary to develop the background for the phenomena under study. It is assumed that the reader has a basic knowledge of applied mechanics and soil mechanics, as well as a general familiarity with the commonly used engineering properties of soils and their determination.

1.2 SCOPE AND ORGANIZATION

The topics covered in this book begin with consideration of soil formation in Chapter 2 and soil mineralogy and compositional analysis of soil in Chapter 3. Water may make up more than half the volume of a soil mass, it is attracted to soil particles, and the interactions between water and the soil surfaces influence soil behavior. Interrelationships between soil, water, and chemicals are developed in Chapter 4.

Fundamentals of soil characterization for engineering purposes are covered in Chapter 5. Because a soil mass is composed of an assemblage of discrete particles that may be of different sizes and shapes and arranged in many ways, the specifics of these arrangements and their properties, termed the soil *fabric,* is an essential consideration. Observing and quantifying these fabrics is the subject of Chapter 6. This is followed in Chapter 7 by an analysis of the transmission of interparticle forces and total and effective stresses and a discussion of why they are important.

The remaining chapters draw on the preceding developments for explanations of phenomena and soil properties of interest in geotechnical and geoenvironmental engineering. The next three chapters deal with those soil properties that are of primary importance to the solution of most geoengineering problems: the flows of fluids, chemicals, electricity, and heat and their consequences in Chapter 8; volume change behavior in Chapter 9; and deformation and strength behavior in Chapter 10. Some special and unique features of soil behavior, arising because of the particulate nature, different fabrics, biogeochemical interactions, and changing environmental conditions are discussed in Chapter 11. In recent years, both the importance and understanding of temperature effects and heat flow in the ground have increased significantly, and these topics are addressed in Chapter 12. Finally, Chapter 13 on time effects on strength and deformation recognizes that soils are not inert, static materials and that how a given soil responds under different rates of loading or at some time in the future may be quite different than how it responds today.

1.3 GETTING STARTED

Find an article about a problem, a project, or issue that involves some aspect of geotechnical soil behavior as an important component. The article can be from the popular press, from a technical journal or magazine, such as the *Journal of Geotechnical and Geoenvironmental Engineering* of the American Society of Civil Engineers, *Géotechnique, The Canadian Geotechnical Journal, Soils and Foundations, ENR (Engineering News-Record)*, or elsewhere.

1. Read the article and prepare a one-page *informative abstract*. (An informative abstract summarizes the important ideas and conclusions. A *descriptive abstract,* on the other hand, simply states the article contents.)
2. Summarize the important geotechnical issues that are found in the article and write down what you believe you should know about to understand them well enough to solve the problem, resolve the issue, advise a client, and the like. In other words, what is in the article that you believe the subject matter in this book should prepare you to deal with? Do not exceed two pages.

PART I

Soil Formation, Composition, Characterization