

**Fourth Edition**

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# Fundamentals of **Soil Behavior**

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**James K. Mitchell**

**Kenichi Soga**

**Catherine O'Sullivan**

**WILEY**





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Fourth Edition

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

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



$i$	unit vector	$L$	latent heat of fusion
$i_c$	chemical gradient	$L$	length
$i_e$	electrical gradient	$L_{ij}$	coupling coefficient or conductivity coefficient
$i_h$	hydraulic gradient	$LI$	liquidity index
$i_t$	thermal gradient	$LI_{eq}$	equivalent liquidity index
$I$	electrical current	$LL$	liquid limit
$I$	intensity	$L_s$	latent heat of fusion of water
$I_1, I_2, I_3$	stress invariants	$m$	slope of relationship between log creep strain rate and log time
$I_G$	coefficient of shear modulus increase with time	$m$	total mass per unit total volume
$I_R$	dilatancy index	$m$	total number of pore classes
$I_v$	void index	$m_c$	mass of clay
$J_c$	chemical flow rate	$m_s$	compressibility of mineral solids under hydrostatic pressure
$J_D$	chemical flow rate		compressibility of mineral solids under concentrated loadings
$J_i$	flux of constituent $i$	$m'_s$	compressibility
$J_i$	value of property $i$ in clay-water system	$m_v$	compressibility of water
$J_s$	flow rate of salt relative to fixed soil layer	$m_w$	mass of water
$J_v$	volume flow rate of solution	$m_w$	constrained modulus or coefficient of volume change
$J_w$	flow rate of water	$M$	metal cations
$J_i^0$	value of property $i$ in pure water	$M$	monovalent cation concentration
$k$	Boltzmann's constant = $1.38045 \times 10^{-23}$ J/°K	$n$	concentration, ions per unit volume
$k$	hydraulic conductivity, hydraulic permeability	$n$	harmonic number
$k$	mean coordination number of a grain	$n$	integer
$k$	selectivity coefficient	$n$	number of grains in an ideal breakage plane
$k$	thermal conductivity	$n$	porosity
$k$	true cohesion in a solid	$n$	total number of pore classes
$k_0$	pore shape factor	$n$	unspecified atomic ratio
$k_c$	osmotic conductivity	$n_0$	concentration in external solution
$k_e$	electro-osmotic conductivity	$n_1$	number of bonds per unit of normal force
$k_h$	hydraulic conductivity	$n_e$	effective porosity
$k_i$	constant characteristic of a property	$n_i$	Refractive index in $i$ direction
$k_r$	relative permeability	$N$	Avogadro's number = $6.0232 \times 10^{23}$ mole <sup>-1</sup>
$k_s$	saturated conductivity	$N$	coordination number
$k(S)$	saturation dependent hydraulic conductivity	$N$	monovalent cation concentration
$k_t$	thermal conductivity	$N$	normal load or force
$k_\theta$	unsaturated hydraulic conductivity	$N$	number of moles of hydration water per mole of ion
$K$	absolute permeability or intrinsic permeability	$N$	number of particles per cluster in a cluster structure
$K$	bulk modulus	$N$	number of weeks since disturbance
$K$	double-layer parameter = $(8\pi n_0 e^2 v^2 / DRT)^{1/2}$	$N$	total number of harmonics
$K$	pore shape factor	$N_1$	number of load cycles to cause liquefaction
$K$	rate of increase in tip resistance in logarithmic time	$N_e$	number of load cycles
$K_0$	coefficient of lateral earth pressure at rest	$N_G$	normalized shear modulus increase with time
$K_a$	coefficient of active earth pressure	$N_s$	moles of water per unit volume of sediment
$K_c$	principal stress ratio	$N_w$	moles of salt per unit volume of sediment
$K_c$	principal stress ratio during consolidation	$OCR$	overconsolidation ratio
$K_d$	distribution coefficient	$p$	constant that accounts for the interaction of pores of various sizes
$K_p$	coefficient of passive earth pressure	$p$	hydrostatic pressure
$K_{so}$	stress-optical material constant		
$K_\alpha$	wavelengths of monochromatic radiation		
$l$	length		
$l$	material thickness		
$l$	total number of pore classes		

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

$u$	pore water pressure	$Z$	elevation or elevation head
$u$	pore water pressure in the interparticle zone	$Z$	number of molecules per second striking a surface
$u$	pressure	$Z$	potential function = $ve\psi_0/kT$
$u$	thermal energy	$\alpha$	angle between $b$ and $c$ crystallographic axes
$u^*$	effective ionic mobility	$\alpha$	directional parameter
$u_0$	initial pore pressure	$\alpha$	disturbance factor
$u_0$	pore water pressure remote from the interparticle zone	$\alpha$	geometrical packing parameter
$U_f$	pore pressure at failure	$\alpha$	inclination of failure plane to horizontal plane
$U$	average degree of consolidation	$\alpha$	slope of the relationship between logarithm of creep rate and creep stress
$v$	flow velocity	$\alpha$	thermal ratio
$v$	frequency of activation	$\alpha$	tortuosity factor
$v$	ionic valence	$\alpha_G$	normalized strain rate parameter
$v$	settling velocity	$\alpha_s$	thermal expansion coefficient of soil solids
$v$	specific volume = $1 + e$	$\alpha_{ST}$	thermal expansion coefficient of soil structure
$v_{ave}$	average flow velocity	$\alpha_w$	thermal expansion coefficient of water
$v_c^0$	specific volume of the pure clay	$\beta$	angle between $a$ and $c$ crystallographic axes
$v_{cs}$	specific volume at critical state	$\beta$	birefringence ratio
$v_h$	apparent water flow velocity	$\beta$	disturbance factor
$V$	area	$\beta$	geometrical packing parameter
$V$	difference in self-potentials	$\beta$	rotation angle of yield envelope
$V$	electrical potential	$\beta_0, \beta_i$	constant characteristic of the property and the clay
$V$	speed	$\chi$	Bishop's unsaturated effective stress parameter
$V$	valence	$\delta$	clay plate thickness measured between centers of surface layer atoms
$V$	voltage	$\delta$	deformation parameter in Hertz theory
$V$	volume	$\delta$	displacement, distance
$V_0$	initial volume	$\delta$	solid fraction of a contact area
$V_A$	attractive energy	$\delta$	relative retardation
$V_{DR}$	volume of water drained	$\delta_p$	particle eccentricity distance
$V_{GS}$	volume of granular solids	$\epsilon$	dielectric constant, permittivity
$V_m$	total volume of soil mass	$\epsilon$	porosity
$V_p$	compression wave velocity	$\epsilon$	strain
$V_R$	repulsive energy	$\dot{\epsilon}$	strain rate
$V_s$	shear wave velocity	$\epsilon_0$	permittivity of vacuum, $8.85 \times 10^{-12} \text{ C}^2/(\text{Nm}^2)$
$V_s$	volume of solids	$\epsilon_1$	axial strain
$V_w$	partial molar volume of water	$\dot{\epsilon}_a$	vertical strain rate in one dimensional consolidation
$V_w$	volume of water	$\epsilon_f$	strain at failure
$w$	water content	$\dot{\epsilon}_{\min}$	minimum strain rate
$w_L, w_l$	liquid limit	$\epsilon_{rd}$	volumetric strain that would occur if drainage were permitted
$w_P, w_p$	plastic limit	$\epsilon_s$	deviator strain
$W$	water content	$\dot{\epsilon}_s$	deviator strain rate
$W$	width	$\epsilon_v$	volumetric strain
$W$	fluid volume	$\dot{\epsilon}_v$	volumetric strain rate
$W$	water transport	$\Delta E$	energy dissipated per cycle per unit volume
$W$	weight	$\phi$	friction angle
$x$	distance from the clay surface	$\phi$	local electrical potential
$X$	distance	$\phi'$	friction angle in effective stress
$X$	friction coefficient	$\phi^b$	angle defining the rate of increase in shear strength with respect to soil suction
$X_i$	driving force	$\phi_c$	characteristic friction angle
$y$	potential function = $ve\Psi/kT$		
$z$	direction of gravity		
$z$	distance from drainage surface		
$z$	electrolyte		
$z$	ionic valence		

$\phi'_{crit}$	friction angle at critical state	$\theta$	volumetric water content
$\phi_e, \phi'_e$	Hvorslev friction parameter	$\theta_m$	volumetric water content at full saturation
$\phi'_f$	friction angle corrected for the work of dilation	$\theta_r$	residual water content
$\phi'_m$	peak mobilized friction angle	$\theta_s$	volumetric water content at full saturation
$\phi'_r$	residual friction angle	$\rho$	bulk dry density
$\phi_{repose}$	angle of repose	$\rho$	charge density
$\phi_v$	apparent specific volume of the water in a clay/ water system of volume $V$	$\rho$	mass density
$\phi_\mu, \phi'_\mu$	intergrain sliding friction angle	$\rho_d$	bulk dry density
$\Phi$	dissipation function	$\rho_T$	resistivity of saturated soil
$\gamma$	activity coefficient	$\rho_w$	density of water
$\gamma$	angle between $a$ and $b$ crystallographic axes	$\rho_W$	resistivity of soil water
$\gamma$	unit weight	$\sigma$	area occupied per adsorbed molecule on a surface
$\dot{\gamma}$	shear strain rate	$\sigma$	double-layer charge
$\gamma_c$	applied shear strain or cyclic shear strain amplitude	$\sigma$	electrical conductivity
$c_d$	dry unit weight	$\sigma$	entropy production
$\Gamma$	double layer charge	$\sigma$	normal stress
$\Gamma$	specific volume intercept at unit pressure	$\sigma$	surface tension of water
$\eta$	dynamic viscosity	$\sigma$	surface charge density
$\eta$	fraction of pore pressure that gives effective stress	$\sigma$	total stress
$\eta_0$	initial anisotropy	$\sigma'$	effective stress
$\kappa$	swelling index	$\sigma'_0$	initial effective confining pressure
$\kappa'$	real relative permittivity	$\sigma_1$	major principal total stress
$\kappa''$	polarization loss, imaginary relative permittivity	$\sigma_1$	tensile strength of the interface bond
$\lambda$	compression index	$\sigma'_1$	major principal effective stress
$\lambda$	correction coefficient for frost depth prediction equation	$\sigma_{1c}$	major principal stress during consolidation
$\lambda$	damping ratio	$\sigma_{1f}$	major principal stress at failure
$\lambda$	decay constant	$\sigma'_{1ff}$	major principal effective stress at failure
$\lambda$	pore size distribution index	$\sigma'_2$	intermediate principal effective stress
$\lambda$	separation distance between successive positions in a structure	$\sigma_3$	minor principal total stress
$\lambda$	wave length of X ray	$\sigma'_3$	minor principal effective stress
$\lambda$	wave length of light	$\sigma_{3c}$	minor principal stress during consolidation
$\lambda_{cs}$	critical state compression index	$\sigma'_{3ff}$	minor principal effective stress at failure
$\mu$	chemical potential	$\sigma'_a$	axial effective stress
$\mu$	coefficient of friction	$\sigma'_{ac}$	axial consolidation stress
$\mu$	dipole moment	$\sigma_{as}$	interfacial tension between air and solid
$\mu$	fusion parameter	$\sigma_{aw}$	interfacial tension between air and water
$\mu$	Poisson's ratio	$\sigma_c$	crushing strength of particles
$\mu$	viscosity	$\sigma_c$	tensile strength of cement
$M$	critical state stress ratio	$\sigma_e$	electrical conductivity
$\nu$	Poisson's ratio	$\sigma'_e$	equivalent consolidation pressure
$\nu_b$	Poisson's ratio of soil skeleton	$\sigma_{eff}$	effective AC conductivity
$\pi$	osmotic or swelling pressure	$\sigma_f$	partial stress increment for fluid phase
$\theta$	angle of bedding plane relative to the maximum principal stress direction	$\sigma'_f$	effective normal stress on shear plane
$\theta$	contact angle	$\sigma_{ff}$	normal total stress on failure plane
$\theta$	geometrical packing parameter	$\sigma'_{ff}$	normal effective stress on failure plane
$\theta$	liquid-to-solid contact angle	$\sigma_h$	electrical conductivity due to hydraulic flow
$\theta$	orientation angle	$\sigma'_{h0}$	initial horizontal effective stress
		$\sigma'_i$	effective stress in the $i$ -direction
		$\sigma'_i$	intergranular stress
		$\sigma'_i$	isotropic consolidation
		$\sigma_{iso}$	isotropic total stress
		$\sigma_{max}$	maximum principal stress
		$\sigma_{min}$	minimum principal stress

$\sigma'_n$	effective normal stress	$\tau_{ff}$	shear stress at failure on failure plane
$\sigma'_p$	preconsolidation pressure	$\tau_i$	shear strength
$\sigma_r$	radial total stress	$\tau_i$	shear strength of contact
$\sigma'_r$	radial effective stress	$\tau_m$	shear strength of solid material in yielded zone
$\sigma'_{rc}$	radial consolidation stress	$\tau_{peak}$	applied shear stress at peak
$\sigma_s$	conductivity of soil surface	$\tau_\alpha$	initial static shear stress
$\sigma_s$	partial stress increment for solid phase	$\nu$	mass flow factor
$\sigma_s$	tensile strength of the sphere	$\nu$	cation valence
$\sigma_T$	electrical conductivity of saturated soil	$\xi$	distance function = $Kx$ , double-layer theory
$\sigma_T, \sigma'_t$	tensile strength of cemented soil	$\xi$	ratio of average temperature gradient in air filled pores to overall temperature gradient
$\sigma_v$	vertical stress	$\psi$	dilation angle
$\sigma'_v$	vertical effective stress	$\psi$	electrical potential
$\bar{\sigma}_{v0}$	overburden vertical effective stress	$\psi$	intrinsic friction angle
$\sigma'_{v0}$	overburden effective stress	$\psi$	matric suction
$\sigma'_{ym}$	maximum past overburden effective stress	$\psi_0$	surface potential of double layer
$\sigma'_{vp}$	vertical preconsolidation stress	$\psi_d$	displacement pressure
$\sigma_W$	electrical conductivity of pore water	$\Psi$	electrical potential
$\sigma_{ws}$	interfacial tension between water and solid	$\Psi$	state parameter
$\sigma_y$	yield strength	$\Psi$	total potential of soil water
$\sigma_\theta$	circumferential stress	$\Psi_0$	electrical potential at the surface
$\tau$	shear strength	$\Psi_s$	gravitational potential
$\tau$	shear stress	$\Psi_m$	matrix or capillary potential
$\tau$	surface tension	$\Psi_p$	gas pressure potential
$\tau$	swelling pressure or matric suction	$\Psi_s$	osmotic or solute potential
$\tau$	undrained shear strength	$\omega$	angular velocity
$\tau_a$	apparent tortuosity factor	$\omega$	frequency
$\tau_c$	applied shear stress	$\omega$	osmotic efficiency
$\tau_c$	contaminant film strength	$\Omega$	true electroosmotic flow
$\tau_{cy}$	undrained cyclic shear stress	$\zeta$	zeta potential
$\tau_d$	drained shear strength		



# CHAPTER 1

## Introduction

### 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.

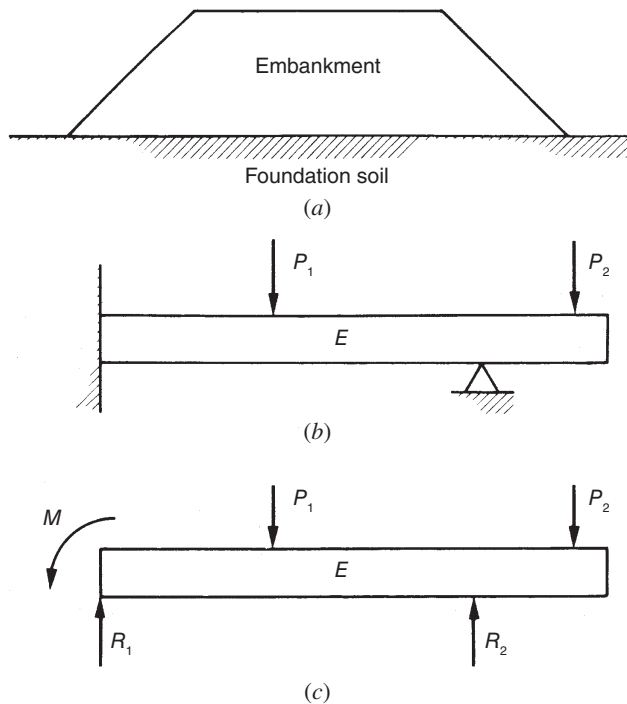


Successful design, construction, and long-term performance of a complex earth embankment dam such as this requires knowledge and understanding of all four dimensions of soil behavior—volume change properties, stress and deformation characteristics, flow of fluid through the materials, and changes in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

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. 1.1a, and a cantilever beam fixed at one end is shown in Fig. 1.1b. The free body of the cantilever beam, Fig. 1.1c, 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



**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 geoenvironmental 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**

