

A scanning electron micrograph (SEM) of soil particles, showing a dense cluster of rounded, irregular grains on the left side of the cover, with the rest of the background being dark and textured.

 **WILEY**

SOILS AND WAVES

**Particulate Materials Behavior,
Characterization and Process Monitoring**

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in collaboration with

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SOILS AND WAVES



Preface

Particulate media such as powders, soils, and food grains are multiphase non-linear systems. Their properties depend on interparticle forces and interactions between the phases. Such materials are challenging for the analyst, the modeler and the experimentalist who attempt to capture their behavior and interpret internal processes.

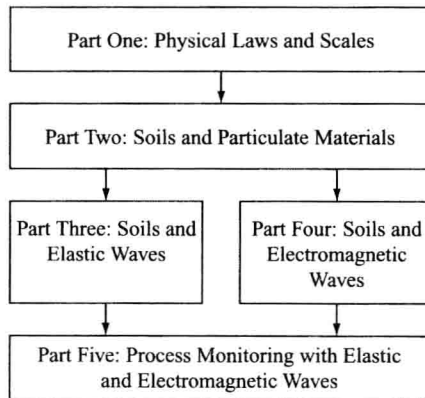
The rapid evolution of technological and analytical tools in the last few decades has enhanced our capabilities to study and to analyze particulate materials. Researchers today have new concepts and paradigms (e.g., self-similarity, percolation), powerful simulation tools (e.g., micromechanics, molecular dynamics), and a new generation of sensors and devices with capabilities not imagined a few decades ago (e.g., micro-electronics, tunneling and atomic force microscopy, spectrum analyzers, tomographers, positron emission, and magnetic resonance imaging).

Low-energy elastic and electromagnetic waves play an important role in the characterization of particulate materials. Waves interact with tested materials producing no permanent residual effects or measurable perturbations to ongoing processes. Furthermore, they allow for the remote characterization of a medium and the tomographic determination of local information from boundary measurements. These observations have important implications for laboratory studies in engineering science, and for field applications in site assessment and process monitoring.

Models are abstractions of reality and are, therefore, uncertain. The scientific revolution at the beginning of the twentieth century has changed our conceptualization of physical phenomena: the mechanical concept of matter has been changed for energy, electrons have become energy states, and electromagnetic phenomena have been explained at a deeper level by quantum electrodynamics, abandoning the wave model predicted in Maxwell's equations. In this book we retain the older 'paradigms' that include the mechanistic conceptualization of matter in the Newtonian sense (including Bohr's atomic model to explain phenomena at the atomic level such as conductivity), Maxwell's equations to interpret electromagnetic phenomena, and the wave model of propagation for small mechanical or electrical perturbations. This choice to preserve the old paradigms reflects the simplicity of these models, the cultural predisposition to understand them, and their ability to explain most phenomena relevant to engineering needs.

In preparing this book we emphasized physical insight and clarity, yet we tried to avoid unrealistic simplifications. Multiple figures illustrate fundamental aspects of behavior. The prevalence of examples from the field of geomaterials reflects the authors' primary field of research; however, concepts presented in this book are applicable to other fields related to particulate media. Suggested reading and selected classical historical references are included at the end of each chapter where the reader can find further information. References cited throughout the text appear at the end of the manuscript. Relevant constants and SI units are summarized in Tables I and II.

This book is divided into five parts. The first part dwells on the problem of scales in relation to soils and waves. In the second part, we review the behavior of particulate materials, distinguishing between fine- and coarse-grained media with emphasis on micro-level justification of macro-level behavior. The third and fourth parts center on the propagation of elastic and electromagnetic waves in particulate materials, addressing phenomena such as complex stiffness and polarization. Laboratory techniques to measure spectral response are discussed in these units. The fifth part presents selected laboratory studies of process monitoring in particulate materials using both elastic and electromagnetic waves. The structure of the book is captured in the following sketch:



A large number of researchers and authors have affected our understanding and have contributed to the body of information presented in this book. The list of references is an acknowledgement of their contribution. Research projects related to concepts addressed in this book have been funded by the following agencies and industrial organizations: NSF (USA), NSERC (Canada), Turkstra Lumber (Canada), INCO (Canada), INTEVEP (Venezuela), ANDRA (France), Shell, and Georgia mining companies. We are grateful to our host institutions: Georgia Institute of Technology, the University of Waterloo, the University of Toronto and Cairo University. In particular, we are indebted to the following individuals for ideas, comments and/or corrections: M. Aloufi, P. Arduino, S. Burns, G. Cascante, G. C. Cho, J. DeJong, A. Díaz-Rodríguez, A. Fernandez, F. Fransisca, D. Fratta,

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Finally, we are most thankful to our families!

Notation

Note: The most common usage is listed; a letter or symbol may have a local meaning within a section or chapter.

α	attenuation coefficient
α	polarizability; α_e electronic; α_i ionic; α_d orientational; α_t thermal
β	multiple uses as fitting parameters (coefficient or exponent)
χ	susceptibility; χ_e electrical; χ_m magnetic
δ	deformation, displacement or distance
δ	loss angle
δ_{ij}	Kronecker's delta
Δ	logarithmic decrement
ε	normal strain
ε	permittivity; ε^* complex; ε' real; ε'' imaginary; $\varepsilon''_{\text{eff}}$ effective imaginary
ε_0	permittivity of free space, $\varepsilon_0 = 8.85 \times 10^{-12} \text{ C}^2/(\text{N} \cdot \text{m}^2) = 8.85 \times 10^{-12} \text{ F/m}$
ϕ	angle of internal shear strength; ϕ_{mob} mobilized; ϕ_{res} residual
γ	shear strain; γ_r reference; γ_t threshold; γ_{td} degradation threshold; γ_{dl} linear threshold; γ_{tr} threshold for residual state
γ	unit weight
γ^*	complex propagation constant
η	fluid viscosity
φ	phase angle
ϑ	thickness of the diffuse double layer; Debye – Hückel length
κ	wave number
κ	relative permittivity; κ^* complex; κ' real; κ'' imaginary; κ''_{eff} effective imaginary
λ	slope of the normal compression line on the $e - \log(p')$ plane
λ	wavelength
λ_{ddl}	surface conduction
μ	friction between particles; friction coefficient
μ	magnetic permeability; μ^* complex; μ' real; μ'' imaginary
μ_{rel}	relative magnetic permeability; μ^*_{rel} complex; μ'_{rel} real; μ''_{rel} imaginary
μ_B	Bohr magneton ($\mu_B = 9.27 \times 10^{-24} \text{ J/T}$)

μ_d	dipole moment
μ_0	magnetic permeability of free space ($\mu_0 = 4 \times 10^{-7}$ H/m)
ν	Poisson's ratio
θ	angle with respect to the normal; phase angle
ρ	mass density
ρ	resistivity
ρ	charge density; ρ_{bound} bound; ρ_s surface; ρ_v volumetric
σ	total normal stress; σ' effective; σ_d deviatoric; σ_0 isotropic; σ'_p preload pressure
σ	electrical conductivity; σ_{eff} effective AC electrical conductivity
σ	standard deviation
τ	relaxation time
τ	shear stress; τ_f ultimate shear strength
ω	angular frequency; ω_{res} resonant frequency; ω_{rel} relaxation frequency
Ψ	dilatancy angle
ζ	zeta potential
a	various local uses (acceleration, radius or size; Henkel's parameter)
A	area; cross-sectional area; surface area
AC	alternating current
A_h	Hamaker constant
A_s	surface area
\mathcal{A}	Skempton's pore pressure parameter
B	bulk modulus
B	magnetic field
B	susceptance
\mathcal{B}	Skempton's pore pressure parameter
c	ionic concentration; c_0 bulk fluid concentration
c	shear intercept; 'cohesion' intercept
cn	coordination number
c_0	speed of light in free space, $c_0 = 3 \times 10^8$ m/s
c_v	coefficient of consolidation or pressure diffusion
C	capacitance
C	specific heat
C_c	coefficient of curvature
C_c	compression index
CEC	counterion exchange capacity
CPE	constant phase element
C_r	recompression index
CSL	critical state line
C_u	coefficient of uniformity
C_v	specific heat per unit volume
d	grain size, particle diameter
d_i	volume fraction of phase i
D	damping ratio

D	diffusion coefficient
D	electric displacement field
D^*	fractal dimension
DC	direct current
\mathcal{D}	Skempton's pore pressure parameter
e	exponential ($e = 2.718$)
e	void ratio
e_0	electron charge ($e_0 = 1.602 \times 10^{-19}\text{C}$)
E	elastic Young's modulus
E	electric field
E	energy; E_p potential energy; E_T thermal energy
f	frequency
F	Faraday's constant ($F = 9.648 \times 10^4\text{C/m}$)
F	force
g	acceleration due to gravity ($g = 9.81\text{ m/s}^2$)
G	conductance
G	gravitational constant ($6.673 \times 10^{-11}\text{N.m}^2/\text{kg}^2$)
G	shear modulus; shear stiffness
G_s	specific gravity
h	Planck's constant ($h = 6.626 \times 10^{-34}\text{Js}$)
H	magnetic field
H	specimen height
i	current
i	gradient
I	mass polar moment of inertia
$\text{Im}()$	imaginary part of the quantity in brackets
j	denotes a complex quantity ($j^2 = -1$)
J	current density
k	Boltzmann's constant ($k = 1.38 \times 10^{-23}\text{J/K}$)
k	spring stiffness
k_h	hydraulic conductivity
K	absolute hydraulic conductivity
K	stress anisotropy; principal stress ratio; K_0 at zero lateral strain
L	distance or length
L	inductance
LI	liquidity index
LL	liquid limit
m	mass
m_e	electron mass ($m_e = 9.11 \times 10^{-31}\text{kg}$)
M	constraint modulus; M^* complex; M' real; M'' imaginary
M	friction parameter in critical state
M	magnetization
M	mass of a mole

n	index of refraction
n	porosity
N_{av}	Avogadro's number ($N_{av} = 6.022 \times 10^{23} \text{mol}^{-1}$)
p	dipole moment
p'	mean effective stress; volumetric stress; effective mean confinement
p_a	atmospheric pressure
P	polarization field
P	power
PI	plasticity index
PL	plastic limit
PLR	preload ratio
q	charge
q	flow rate
q	shear or deviator stress; distortional stress
Q	quality factor
r	distance; radius
R	particle or pore radius
R	reflection coefficient
R	resistance
R	universal gas constant ($R = 8.314 \text{J}/(\text{K} \cdot \text{mol})$)
R_{DL}	double layer repulsion force
$\text{Re}()$	real part of the quantity in brackets
S	degree of saturation
S_a	specific surface by mass; S_v specific surface by volume
S_d	skin depth
t	time
$\tan \delta$	loss tangent
T	period
T	temperature
T	transmission coefficient
T_s	surface tension
u	deformation or displacement; particle motion
u	pore fluid pressure; u_{ex} excess pore water pressure
U	stored energy
V	electrostatic potential; V_0 surface potential; V_{st} Stern potential
v	linear velocity
V	volume
V	velocity of elastic waves; V_P P-wave; V_s S-wave; V_{ph} phase velocity; V_R Rayleigh wave; V_L longitudinal wave
w	water content; w_n natural water content
W	weight
W	work
x	displacement or distance; x' velocity; x'' acceleration

X	reactance
Y	admittance; Y^* complex
z	height
z	ionic valence
z	mechanical impedance (continuum)
Z	impedance lumped element; Z^* complex; Z' real; Z'' imaginary

Table I Constants

Quantity	Symbol	Value
Electron charge	e_0	$1.602 \times 10^{-19} \text{ C}$
Electron mass	m_e	$9.1091 \times 10^{-31} \text{ kg}$
Bohr magneton	μ_B	$9.273 \times 10^{-24} \text{ J/K}$
Boltzmann constant	k	$1.381 \times 10^{-23} \text{ J/K}$
Avogadro's number	N_{av}	$6.022 \times 10^{23} \text{ mol}^{-1}$
Gas constant	R	$8.314 \text{ J/(mol} \cdot \text{K)}$
Faraday's constant	F	$9.6485 \times 10^4 \text{ C/mol}$
Permeability of free space	μ_0	$4\pi \times 10^{-7} \text{ H/m}$
Permittivity of free space	ϵ_0	$8.854 \times 10^{-12} \text{ F/m}$
Characteristic impedance of free space	z_0	377Ω
Speed of light in vacuum	c_0	$2.998 \times 10^8 \text{ m/s}$
Atmospheric pressure	p_{atm}	101.325 kPa
Zero degrees celsius	0°C	273.15 K
Gravitational constant	G	$6.673 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2$

Notes:

- $1 \text{ \AA} = 1 \text{ \AA ngstr\AA om} = 10^{-10} \text{ m}$
- Avogadro's number is the number of elementary entities in one mole. The elementary entity must be specified; it may be atoms, molecules, ions, electrons or other particles. Values found for Avogadro's number range within 1% of the listed value.
- Relationships between constants: $Re_0^2N_{av} = kF^2$, $F = e_0N_{av}$, $R = kN_{av}$.

Table II SI system – units

Temperature	kelvin	K	
Length	meter	m	
Time	second	s	
Mass	kilogram	kg	
Force	newton	N	$\text{kg}\cdot\text{m}/\text{s}^2$
Pressure	pascal	Pa	N/m^2
Work and energy	joule	J	$\text{N}\cdot\text{m}$
Power	watt	W	J/s
Electric current	ampere	A	
Electric charge	coulomb	C	$\text{s}\cdot\text{A}$
Electric potential	volt	V	W/A
Electric resistance	ohm	Ω	V/A
Electric conductance	siemens	S	A/V
Capacitance	farad	F	C/V
Permittivity			F/m
Magnetic flux	weber	Wb	$\text{V}\cdot\text{s}$
Magnetic flux density	tesla	T	Wb/m^2
Inductance	henry	H	Wb/A
Magnetic field			A/m
Permeability			H/m
Concentration			mol/m^3
Frequency	hertz	Hz	cycle/s

Common SI Prefixes

Tera	T	10^{12}	milli	m	10^{-3}
Giga	G	10^9	micro	μ	10^{-6}
Mega	M	10^6	nano	n	10^{-9}
Kilo	k	10^3	pico	p	10^{-12}

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