Earth Science for Civil and Environmental Engineers

This carefully targeted and rigorous new textbook introduces engineering students to the fundamental principles of applied earth science, highlighting how modern soil and rock mechanics, geomorphology, hydrogeology, seismology and environmental geochemistry affect geotechnical and environmental practice. Key geological topics of engineering relevance, including soils and sediments, rocks, groundwater and geologic hazards, are presented in an accessible and engaging way. A broad range of international case studies add real-world context and demonstrate practical applications in field and laboratory settings to guide site characterization. End-of-chapter problems are included for self-study and evaluation, and supplementary online materials include electronic figures, additional examples, solutions, and guidance on useful software.

Featuring a detailed glossary introducing key terminology, this text requires no prior geological training and is essential reading for senior undergraduate or graduate students in civil, geological, geotechnical and geoenvironmental engineering. It is also a useful reference and bridge for earth science graduates embarking on engineering geology courses.

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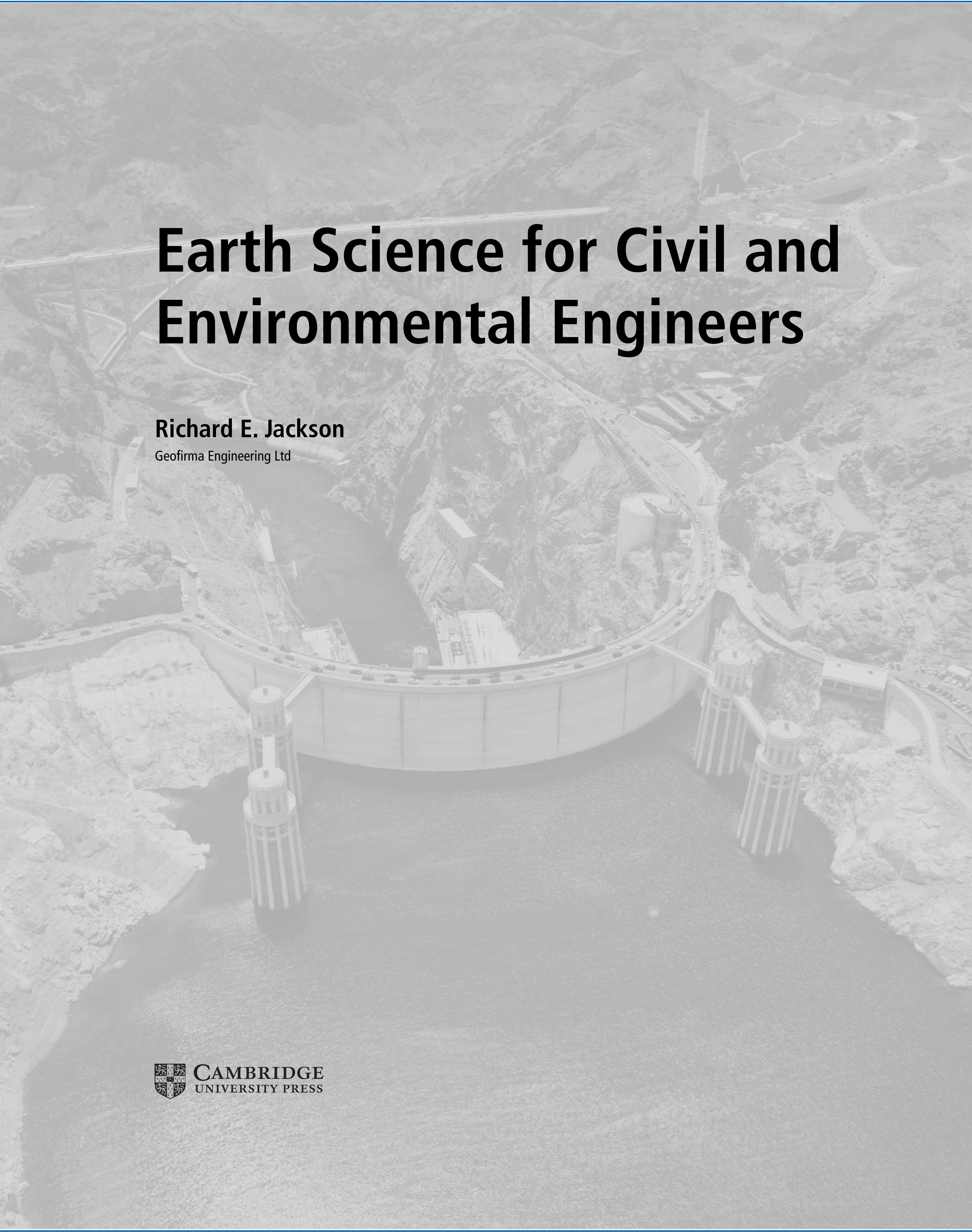

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PREFACE

Motivation and Objectives

The purpose of this book is to introduce civil and environmental engineering students – and those active in engineering – to the fundamental principles of the earth sciences as they affect their practice. In particular, this book is intended for the use of geotechnical and geoenvironmental students and those in that practice. Hopefully, the reader will come to appreciate the complex problems that exist in engineering practice in a geological environment and find them intellectually rewarding. It also seeks to persuade the engineer that he or she should not try to solve all their problems without the advice of geoscientists. Rather, it is written to give the engineer an appreciation of the fundamentals of geological processes in order to work more effectively in a team comprising engineers and geoscientists.

This book is divided into four parts: Rocks as engineering materials; Soils and sediments; Groundwater; and Geological hazards. Additionally, the book contains supplementary material on a website, where additional case histories may be studied and where useful software is discussed. In many cases, this software is available free to the user; in other cases, the software is available at reasonable prices from software houses that cater to engineers. Chapters end with a set of questions to test understanding of the topics covered. Answers to the questions are to be found online in the material reserved for instructors.

The objectives of the four parts of this book may be summarized as follows:

Part I: Rocks as engineering materials. To understand the structure and properties of rocks as engineering materials in foundations, mineral extraction and waste disposal. This part necessarily begins with a discussion of minerals and the composition of rocks composed of these minerals before introducing the reader to geological structures and maps. The next chapter introduces the science of rock mechanics to allow the reader to appreciate its role in slope stability, tunnelling, waste disposal and seismicity, among other areas of engineering importance. Finally, Part I ends with a discussion of how engineers and geoscientists characterize the properties of rocks important in their work.

Part II: Soils and sediments. To appreciate how soils and sediments are produced, transported and obtain their physical-chemical properties. This part introduces the engineer to weathering, glacial and fluvial processes and the characterization of soils and sediments. Furthermore, Part II devotes a chapter to assist the geoenvironmental engineer in understanding how geochemical processes and mineralogy can affect his or her work.

Part III: Groundwater. To understand groundwater flow and the cause and development of groundwater contamination. Here we consider the nature of hydraulic conductivity, groundwater flow systems, aquifers and aquitards. These discussions are followed by a review of the processes that generate groundwater quality, whether natural or contaminated.

Part IV: Geological hazards. To recognize the conditions under which geological hazards exist and may threaten lives and infrastructure. The hazards considered include land subsidence due to extraction of groundwater and minerals and to karst development, earthquakes and active faults, landslides in their many forms and coastal hazards, such as storm surges and beach erosion in an era of climate change.

Teaching Earth Sciences to Engineers

Geotechnical engineers face problems of enormous complexity. When the late John Harvey wrote the predecessor of this book – *Geology for Geotechnical Engineers* – in the early 1980s, the tunnel in the chalk beneath the English Channel linking France and England had not yet been started, and it was not completed until 1990. Vastly more difficult tunnels have been completed since, such as those in faulted rock in Taiwan, the Austrian Alps and Greece. Today, geotechnical engineers sometimes operate the tunnel boring machines, so complex has their task become. Geotechnical engineers have also learned much about protecting pipelines and transportation corridors from landslides and from seismic shock. Even if we are not quite ready to pronounce on the magnitude and timing of the next major displacement of the San Andreas Fault, when a magnitude 7.9 earthquake ruptured the Denali Fault in Alaska in 2002 and moved 4 m laterally and 0.5 m vertically, the Trans Alaska Oil Pipeline did not rupture. In fact, the pipeline had been designed to withstand 6.1 m of horizontal displacement and 1.5 m of vertical displacement at the location where the fault crossed the pipeline.

Similarly, today, geoenvironmental engineers design landfills, deep geological repositories and mine-tailings sites for the safe storage of hazardous wastes. Before geoenvironmental engineering developed, it was common for hazardous-waste sites to leak contaminants to groundwater and cause the closure of nearby public water-supply wells or to streams and cause fish kills in rivers.

Nevertheless, even today, many civil engineers graduate and enter practice without any academic introduction to the applied earth sciences irrespective of the onus on the engineer to protect public safety. Despite the advice of some of the greatest geotechnical engineers and engineering geologists of the twentieth century, there is no requirement for civil engineers to take a course in geology as applied to engineering in the USA; the situation is better in the UK and Canada, and perhaps elsewhere.

Karl Terzaghi, the father of geotechnical engineering, recommended “a two-semester course combined with field trips” taught by “a geologist who appreciates the requirements of engineers and an engineer who has learned from personal experience that geology is indispensable in the practice of his profession” (cited by Proctor, 1981). While acknowledging the need for natural science courses in the undergraduate civil engineering curriculum, the American Society of Civil Engineers (ASCE, 2008) merely suggests that geotechnical and environmental engineers would be well served by taking an introductory course in geology and geomorphology.

However, a typical elective course in physical geology is not necessarily helpful in that the lecturer is unlikely to have experience of geologic practice in engineering projects, because such lecturers are rare in earth science or civil engineering departments. Courses in introductory physical geology should be considered part of the liberal education of the engineer, not as preparation for engineering practice where public safety is the responsibility of the engineer.

This book subscribes to Terzaghi’s opinion that geological training for civil engineers is essential to a civil engineer’s education – in particular for those entering geotechnical and geoenvironmental practice – and therefore is not marginal to the engineer’s future career. It has developed from John Harvey’s earlier textbook (Harvey, 1982), which was based upon his lectures given to undergraduate civil engineers at the former Plymouth Polytechnic, now the University of Plymouth, in England. It has been written on the basis of the author’s experience in practice in North America and through his links to European workers in environmental and engineering geoscience. Some of Harvey’s original text remains in Chapter 2 and is acknowledged here to honour his role in teaching engineers.

One implicit goal of the book is to develop some preliminary judgement in evaluating geological phenomena. Here we will follow the advice of Terzaghi’s colleague, Ralph Peck, late Professor of Geotechnical Engineering at the University of Illinois, who stressed the need for empiricism and theory in the development of engineering judgement (Peck, 1991). The former tells us what works and what does not, while the latter provides guidance when the engineer must project designs into unknown empirical territory. Judgement in decision making is not something that comes with an engineering degree; it is progressively learned. John Burland (2007), Emeritus Professor of Soil Mechanics at Imperial College, London, refers to this as “well-winnowed experience” (see Figure 1.1).

Richard Goodman of the University of California wrote (Goodman, 1993):

> No doubt, mastering advanced engineering mathematics or thermodynamics is “harder” for some students than understanding the principles of engineering geology. But in the practice of engineering, geology may prove to be the harder subject. The penalties for geologic mistakes can be severe, whereas the confidence that comes from having made the right choice cannot be obtained from a formula or theory. In my experience, most engineering students are more at home with formulas and analysis than with colors and grades of truth.

A second implicit goal of this book is to address the need to weave hydrogeological principles into geotechnical and geoenvironmental practice. In his brief history of geotechnical engineering, Burland (2012a) cited Terzaghi’s complaint of 1939 that “in engineering practice difficulties with soils are almost exclusively due, not to the soils themselves, but to the water contained in their voids. On a planet without any water there would be no need for soil mechanics”. Thus, Burland (2007) had earlier noted of geotechnical failures associated with site investigations that “nine failures out of ten result from a lack of knowledge about the ground profile – often the groundwater conditions”.

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Here I try to provide a physical context to interpret variations in hydraulic head and hydraulic gradient that might assist geotechnical engineers in site investigations. Splendid examples of such practice have been published recently for landslide sites in Western Canada (Eshraghian et al., 2008) and Northern Ireland (Hughes et al., 2016) and by Wyllie (2018) in his revision of Hoek and Bray's *Rock Slope Engineering*. Burland (2007) cites other examples from Terzaghi where hydrogeological phenomena – high heads and piping – complicated geotechnical practice; Burland (2012b) describes similar issues in his own work in guiding the design of the underground car park beneath the Houses of Parliament in London. Furthermore, hydrogeology has become central both to the practice of geoenvironmental engineering, where landfills and mine-tailings facilities must be designed and plumes of contaminated groundwater controlled and remediated, and to the control of land subsidence from over-extraction of groundwater and enhanced dissolution of karst rock.

In the pages that follow, we shall bear in mind ten areas of competency identified by Professor Allen Hatheway (2005), formerly of the Missouri School of Mines, as being required of the young engineer about to enter practice:

- an ability to define the physical properties and characteristics of soils, rock – especially weak rock – and groundwater;
- an appreciation of the manner in which these materials are found in nature;
- an appreciation of the regional geomorphology as the expression of the combined effects of climate, weathering and the sum history of all geologic forces and phenomena over history on the geology of the region;
- an understanding of how geological field data are collected, tested, evaluated, interpreted and then converted to specifications concerning the properties of the site;
- a sense of how anomalies occur routinely in geological materials and how such features can alter, disturb or remove what is most predictable about subsurface interpretations and projections;
- a realization of how geologic discontinuities can alter the properties of geological materials;
- a realization of how the presence of water in geological materials can effectively influence the nature of a site in terms of the construction and performance of engineered works;
- an appreciation of how dynamic earth processes are continually bringing change to the landscape and to the subsurface;
- a sense of the nature of risk as it relates to the potential for the presence and potential impact of undetected geologic features, or the absence thereof; and
- an appreciation of how to prepare a scope of work to seek geological specification of the nature of the proposed construction location, i.e., site characterization.

Like Terzaghi, the geotechnical engineer is urged to make geology an abiding interest. Ruth Doggett Terzaghi, his spouse, used her skills in the petrography of concrete and soils to advise the founder of soil mechanics. Perhaps this book will suffice as an introduction to the applied earth sciences for young engineers – and marriage to a geologist will not be necessary!

Readership

This book is suitable for (i) undergraduates in their final years of their degree course, (ii) graduate students entering geotechnical and/or geoenvironmental engineering courses and (iii) engineers in training and those beginning geotechnical and geoenvironmental practice. It is my belief that earth science is best introduced to engineering students following (i) their introduction to practice through work terms or summer jobs and (ii) their education in fluid, solid and soil mechanics. It is then that they can see that geological processes are cut from the same cloth as taught in engineering mechanics.

Earth Science for Civil and Environmental Engineers is intended to be suitable for those entering an M.Sc. or M.S. degree program – referred to elsewhere as MSCE, M.Eng. or MASc – in these engineering subdisciplines and those entering practice who have not had the benefit of earlier training in the applied earth sciences. Because licensing of US engineers may in future require an M.S. degree or equivalent, this book may become useful as the civil engineering profession in the USA develops the necessary "Body of Knowledge for Professional Practice" (ASCE, 2008) and engineering students in Europe enter new courses – often in the English language – guided by the Bologna process.

Terminology

The terminology used in this book is broadly North American, although some specific British usage is acknowledged, e.g., *superficial* rather than *surficial* deposits. Common geoscientific terms that are printed in **bold** in the text should be memorized: many are defined in the glossary at the end of the book; the definitions of others may be found in Bates and Jackson (1984). The term *geoenvironmental* is used to identify those issues that concern environmental engineers but are confined to the subsurface. Its use by the ASCE, as in their *Journal of Geotechnical and Geoenvironmental Engineering*, indicates that it is well established at least in the English-speaking world. Some terms in this book may strike American readers as somewhat unusual but it is important that they learn to understand documents written in English by the international engineering community because so much important work originates outside America.

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LIST OF SYMBOLS USED IN EARTH SCIENCE

a	annum or year; annual rate as in mm/a or m/a
a, a_c, a_{max}	ground acceleration (seismic) (m^2/s)
$a(f)$	acceleration spectral density function for stochastic model of ground motion, ground acceleration as a function of frequency of waveform
a_i	activity coefficient of ion i
b	aquifer thickness (m)
C	concentration of an analyte, in Chapter 12
C, C_0, C_s	celerity of sequence of wave crests in deep (0) or shallow (s) water, in Chapter 16 (m/s)
C	clay in the USCS of soil textures, e.g., GC, CH and CL for clayey gravel, high-plasticity clay and lean clay, respectively
C_D	damping parameter in slug testing (dimensionless)
$C_{e,i}$	effective solubility of an NAPL
C_H	Hazen coefficient (dimensionless)
$C_{s,i}$	aqueous solubility of an NAPL
C_u	uniformity coefficient (dimensionless)
c'	effective cohesion in a Mohr–Coulomb strength analysis (kPa)
cP	centipoise (unit of viscosity)
c_v	coefficient of consolidation (m^2/s)
D	darcy (unit of permeability in petroleum engineering, in Chapter 11)
D	deuterium (^{2}H)
D_H	hydraulic diameter of stream channel (m)
$D_{i,j}$	dispersion tensor, in Chapter 12 (m^2/s)
D_m	coefficient of molecular diffusion (m^2/s)
D_N	Newmark displacement (cm)
d	grain-size diameter (m)
d	slip distance in an earthquake (m)
d_{min}	minimum grain-size diameter in sieving (m)
d_{10}	grain-size diameter of which 10% of the grains are finer than (m)
E	Young's modulus of elasticity (Pa)
E	wave energy per unit surface area, in Chapter 16 (J/m^2)
E_H	redox potential, in Chapter 7 (V)
E_m	rock mass deformation modulus (Pa)
E_s	strain energy released by an earthquake (J or N m)
E_w	bulk modulus of water (Pa^{-1} or m^2/N)
e	void ratio
e_{max}	maximum void ratio (dimensionless)
F	force, as in F_T or F_N, in Part I (N)
F_D, F_L	drag and lift coefficients, in Chapter 9 (N)
F	fine facies, i.e., silts and clays, in Parts II and III, see Table 11.5
FS	factor of safety
f_c	seismic-source corner frequency, number of wave cycles per second (Hz)
f_s	sleeve resistance in cone penetration testing
G	gravel facies, in Chapter 9; and in USCS terminology as GW, GP, GM and GC for well-graded, poorly graded, silty and clayey gravel, respectively
G_s	specific gravity of soil grains (dimensionless)
g	acceleration of gravity (m/s^2)
H	hydrogen, as in pH or H_2O
H_0	initial water-level change in a slug test (m)
H_b	breaking wave height, in Chapter 16 (m)
H_c	minimum thickness for the dense flow phase of a turbidity current to begin migration (m)
H_{max}	maximum wave height, in Chapter 16 (m)
h	hydraulic head (m)
h_e	environmental water head (m)
h_f	equivalent fresh-water hydraulic head (m)
h	water depth, in Chapter 16 (m)
I	inflow or recharge rate in Figure 11.9 (m/s)
I	major textural component of hydrofacies, in Chapter 9
I_a	Arias intensity, in Chapter 15 (m/s)
I_L	index of liquidity in Atterberg limits (%)
I_P	index of plasticity in Atterberg limits (%)
i	well-loss exponent (dimensionless)
i	angle of inclination of rough surface in Patton's principle, in Chapter 4

K	hydraulic conductivity (m/s)
K_0	saturated hydraulic conductivity; a term used only in the context of unsaturated soils (m/s)
K_h	hydraulic conductivity in the horizontal direction (m/s)
K_v	hydraulic conductivity in the vertical direction (m/s)
$K_{x,y,z}$	hydraulic conductivity in x, y and z directions (m/s)
K_f	hydraulic conductivity of a fracture, in Chapter 4 (m/s)
K	average ratio of horizontal to vertical total stresses, in Chapter 4
K_D	distribution coefficient of a contaminant (m^3/kg)
K_{eq}	equilibrium constant, in Chapter 7
K_{s0}	solubility product at zero ionic strength
K_{AD}	conditional equilibrium sorption constant
K_D	sorption distribution coefficient
K'	average ratio of horizontal to vertical effective stresses, in Chapter 4
K_f	hydraulic conductivity of uniformly fractured rocks, in Chapter 4 (m/s)
K_{oc}	organic carbon partition coefficient (mL/g)
k	specific or intrinsic permeability (m^2; darcy in petroleum engineering)
ka	thousand years ago
k_f	permeability of uniformly fractured rocks, in Chapter 4
k_{rw}, k_{rd}	relative permeabilities of groundwater and NAPL (dimensionless)
L	original thickness of soil or rock sample under compression (m)
L	fault length, in Chapter 14
L_{SR}	length of surface rupture along fault (km)
L, L_0	wavelength, in Chapter 16
L_0	the deep-water wavelength (m)
L_e	effective length of the water column in slug testing (m)
L_{SR}	surface rupture length of a fault (km)
M	molality, in Chapter 7
M	silt, in Chapter 10, as in MH and GM, silt with high elasticity and silty gravel, respectively
MAW	multiple aquifer well
M_0	seismic moment (N m, i.e., J)
M_W	moment magnitude; Richter magnitude
M_L	moment magnitude
M_W	surface-wave magnitude
M_S	empirical measure (dimensionless)
m	mass of object (kg)
mD	millidarcy (unit of permeability in petroleum engineering)
m_i	molarity, in Chapter 7
Myr	duration in million years of a geologic event
n	porosity
n_e	effective porosity
n_f	fracture porosity, in equation (5.2)
O	organic matter, in Chapter 10; in USCS as OL and OH for organic silt and organic clay, respectively
O	oxygen, as in dissolved oxygen, in Chapters 7 and 12; or oxygen-18, in Chapters 8 and 12
P	poise (unit of viscosity, in Chapter 11)
P	partial pressure, as in P_{CO_2}, in Chapter 7
$P^\star$	period of oscillation of sinusoid in temperature, in Chapter 8
P_b	wave power in watts per metre of shoreline (W/m)
P_D, P_d	percentage of soil particles retained by consecutive sieves of sizes D and d, in Chapter 10
PHA	peak horizontal acceleration (g)
Pt	peat in USCS of soil textures, in Chapter 10
p	fluid pressure (Pa)
p_w	pore pressure (Pa)
p_c	capillary pressure (Pa)
$p(d)$	Tóth's pore pressure profile (Pa)
p_e	entry pressure (Pa)
p_f	fracture pressure (Pa)
p_r	reopening pressure (Pa)
per mil, ‰	parts per thousand
Q	total fluid discharge or flow rate (m^3/t)
q	specific discharge, also known as Darcy flux, i.e., Q/A (m^3/m^2 t)
q_c	sleeve resistance in cone penetration testing
q_d, q_w	flow rates of DNAPL and groundwater in a porous medium (L^3/t)
R	recession rate of coastal cliffs or bluffs, in Chapter 16 (m/a)
R_f	retardation factor of a contaminant versus groundwater (dimensionless)
$R(t)$	residual component of the measured sea level (m)
REV	representative elementary volume
RQD	rock quality designation (%)
Sal	salinity of pore water, in Chapter 8 (g/L)
SSA	specific surface area of a soil sample (m^2/kg)

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S	sand facies, in Table 11.5
S	shear force applied to the fracture, in Chapter 4 (N)
S	fluid saturation, fractional or percentage of pore volume
S_r	specific retention, fractional or percentage of total soil or rock volume
S_y	specific yield, fractional or percentage of total soil or rock volume
S_w	water saturation, fractional or percentage of pore volume, in Part III
S	shear waves, in Chapter 14
S_H	horizontal component of shear wave
S_V	vertical component of shear wave
S_t	sensitivity of clay sample, in Chapter 8 (dimensionless)
S	storativity, in Part III (dimensionless)
SI	saturation index of a mineral in aqueous solution, in Chapter 7
s_s	specific storage, in Part III (m^{-1})
s, s_u, s_{ur}	shear strength terms, in Parts II and IV (kPa)
T	transmissivity, in Part III (m^2/s)
T, $\overline{T}_s$, T_{amp}	temperature terms, in Chapter 8
T	wave period, in Chapter 16 (s)
$T(t)$	component of sea level associated with astronomical tide (m)
T_D	DNAPL thickness causing penetration (m)
t	time
U	uniformity coefficient (dimensionless)

UCS	unconfined or uniaxial compressive strength, often denoted as q_u, C_0 or σ_c (MPa)
$\dot{u}$	long-term slip rate of an active fault (mm/a)
V	mean streamflow velocity, in Chapter 9
V_p	pore volume (m^3)
V_{pm}	volume of porous medium, pore volume, etc. (m^3)
V_s	volume of solids (m^3)
V_w	volume of groundwater (m^3)
v	velocity, average linear velocity of groundwater, in Part III (m/s)
v_S	S-wave velocity (km/s)
v_P	P-wave velocity (km/s)
vol	volume of water entraining a particle (m^3)
w	water content
w_L, w_P	liquid limit and plastic limit, in Atterberg limits, in Part II (%)
w_0	settling velocity of a stream particle (mm/s)
$w(t)/H_0$	normalized head change in slug test, in Chapter 11
X_i	mole fraction of compound *i*, in Chapter 12
$X(t)$	measured sea level (m)
y	displacement of a sinusoidal wave (m)
$\ddot{y}$	acceleration of a point by seismic vibration ($\mathrm{m/s}^2$)
$Z_0(t)$	mean sea level over time (m)
$\dot{Z}$	erosion rate (m/s)
z	elevation head, in Part III (m)
z, z_{active}, $z_\star$	depth terms, in Chapter 8

LIST OF GREEK SYMBOLS

α	compressibility of porous medium (Pa^{-1} or m^2/N)
α_L, α_T	longitudinal and transverse dispersivities (m)
β	angle of the failure plane in Mohr–Coulomb criterion (°)
β	compressibility of water (Pa^{-1} or m^2/N)
γ, γ_w	specific or unit weight of soil or fluid (kN/m^3)
Δp_w	excess pore pressure induced by seismic shaking (Pa)
ϵ_a	axial strain (dimensionless)
ϵ_l	lateral strain (dimensionless)
$\eta(x, t)$	displacement of water surface from mean sea level, in Chapter 16 (m)
θ	fractional moisture content of soil, referenced to porosity or angle of slope
κ	compressibility bulk modulus (Pa)
μ	dynamic viscosity (Pa s)
μ	coefficient of friction in Mohr–Coulomb criterion
μ	shear or rigidity modulus, in Chapter 14 (Pa)
μ_p	plastic viscosity of a non-Newtonian fluid (Pa s)
ν	kinematic viscosity, in Chapter 10 (m^2/s)
ν	Poisson's ratio, in Chapters 1 and 4 (dimensionless)
ρ	fluid density (kg/m^3)
ρ_f, ρ_s	density of fresh water and of salt water (kg/m^3)
ρ_d	dry bulk density (kg/m^3)
ρ_s	particle density (kg/m^3)
ρ_{avg}	average density of water between two depths (kg/m^3)
σ	stress
σ_a	axial stress
σ_e	effective stress
σ_n	normal stress
σ_v	vertical stress
$\sigma_{Hmax}, \sigma_{Hmin}$	maximum and minimum horizontal stresses (Pa)
σ_c	compressive strength of rock
σ_{ci}	laboratory intact uniaxial compressive strength
σ_{cm}	rock mass uniaxial compressive strength
σ	angular frequency of waves (1/s, Hz)
τ	shear stress (Pa)
τ_h	horizontal cyclic shear stress (Pa)
τ_0	cohesion, in Mohr–Coulomb criterion or average bed shear stress, in Chapter 9 (Pa)
τ_{fs}	frictional force per unit area (Pa)
τ_*	Shields parameter (Pa)
τ'	time required for >90% of ultimate compaction
τ_y	yield strength of a non-Newtonian fluid (Pa)
Φ	fluid potential (m^2/s^2)
ϕ	friction angle, in Chapters 1, 4 and 15 (°)
ϕ'	effective friction angle in shear-strength tests (°)
ϕ'_r	residual strength friction angle for drained samples, in Part II (°)
ψ	soil–water tension or suction (Pa)
ω	stream power per unit bed area (W/m^2)
ω	wave power or energy flux in watts per meter of wave, in Chapter 16 (W/m)