

Fundamentals of Soil Physics

This page intentionally left blank

Fundamentals of Soil Physics

DANIEL HILLEL

DEPARTMENT OF PLANT AND SOIL SCIENCES
UNIVERSITY OF MASSACHUSETTS
AMHERST, MASSACHUSETTS



ACADEMIC PRESS

A Subsidiary of Harcourt Brace Jovanovich, Publishers

New York London Toronto Sydney San Francisco

COPYRIGHT © 1980, BY ACADEMIC PRESS, INC.
ALL RIGHTS RESERVED.
NO PART OF THIS PUBLICATION MAY BE REPRODUCED OR
TRANSMITTED IN ANY FORM OR BY ANY MEANS, ELECTRONIC
OR MECHANICAL, INCLUDING PHOTOCOPY, RECORDING, OR ANY
INFORMATION STORAGE AND RETRIEVAL SYSTEM, WITHOUT
PERMISSION IN WRITING FROM THE PUBLISHER.

ACADEMIC PRESS, INC.
111 Fifth Avenue, New York, New York 10003

United Kingdom Edition published by
ACADEMIC PRESS, INC. (LONDON) LTD.
24/28 Oval Road, London NW1 7DX

Library of Congress Cataloging in Publication Data

Hillel, Daniel.
Fundamentals of soil physics.

Bibliography:
Includes indexes.
1. Soil physics. I. Title.
S592.3.H54 631.473 80-16688
ISBN 0-12-348560-6

PRINTED IN THE UNITED STATES OF AMERICA

81 82 83 9 8 7 6 5 4 3 2

*Dedicated to Rachel,
who has made my labor of seven years,
as that of Patriarch Jacob,
seem but a few days.*

This page intentionally left blank

Contents

PREFACE	xiii
ACKNOWLEDGMENTS	xvii

Part I: BASIC RELATIONSHIPS

1. The Task of Soil Physics	3
2. General Physical Characteristics of Soils	
A. Introduction	6
B. Soil Physics	7
C. Chemical and Physical Aspects of Soil Productivity	7
D. Soil as a Disperse Three-Phase System	8
E. Volume and Mass Relationships of Soil Constituents	9
F. The Soil Profile	14
Sample Problems	17
3. Properties of Water in Relation to Porous Media	
A. Introduction	21
B. Molecular Structure	22
C. Hydrogen Bonding	24
D. States of Water	25
E. Ionization and pH	27
F. Solvent Properties of Water	29
G. Osmotic Pressure	31
H. Solubility of Gases	34
I. Adsorption of Water on Solid Surfaces	35
J. Vapor Pressure	37

K. Surface Tension	40
L. Curvature of Water Surfaces and Hydrostatic Pressure	42
M. Contact Angle of Water on Solid Surfaces	43
N. Capillarity	45
O. Density and Compressibility	47
P. Viscosity	48
Sample Problems	50

Part II: THE SOLID PHASE

4. Texture, Particle Size Distribution, and Specific Surface

A. Introduction	55
B. Soil Texture	56
C. Textural Fractions (Separates)	56
D. Soil Classes	59
E. Particle Size Distribution	60
F. Mechanical Analysis	62
G. Specific Surface	65
Sample Problems	68

5. Nature and Behavior of Clay

A. Introduction	71
B. Structure of Clay	71
C. The Principal Clay Minerals	74
D. Humus: The Organic Constituent of Soil Colloids	76
E. The Electrostatic Double Layer	77
F. Ion Exchange	81
G. Hydration and Swelling	84
H. Flocculation and Dispersion	87
Sample Problems	90

6. Soil Structure and Aggregation

A. Introduction	93
B. Types of Soil Structure	94
C. Structure of Granular Soils	95
D. Structure of Aggregated Soils	97
E. Additional Factors Affecting Aggregation	101
F. Characterization of Soil Structure	103
G. Aggregate Stability	108
H. Soil Crusting	112
I. Soil Conditioners	113
J. Hydrophobization of Soil Aggregates	115
Sample Problems	117

Part III: THE LIQUID PHASE

7. Soil Water: Content and Potential

A. Introduction	123
B. The Soil-Water Content (Wetness)	124
C. Measurement of Soil Wetness	125
D. Energy State of Soil Water	134
E. Total Soil-Water Potential	136
F. Thermodynamic Basis of the Potential Concept	138
G. Gravitational Potential	140
H. Pressure Potential	141
I. Osmotic Potential	144
J. Revised Terminology	144
K. Quantitative Expression of Soil-Water Potential	145
L. Soil-Moisture Characteristic Curve	148
M. Hysteresis	152
N. Measurement of Soil-Moisture Potential	155
Sample Problems	162

8. Flow of Water in Saturated Soil

A. Laminar Flow in Narrow Tubes	166
B. Darcy's Law	168
C. Gravitational, Pressure, and Total Hydraulic Heads	172
D. Flow in a Vertical Column	174
E. Flow in a Composite Column	176
F. Flux, Flow Velocity, and Tortuosity	177
G. Hydraulic Conductivity, Permeability, and Fluidity	178
H. Limitations of Darcy's Law	181
I. Relation of Conductivity and Permeability to Pore Geometry	183
J. Homogeneity and Isotropy	185
K. Measurement of Hydraulic Conductivity of Saturated Soils	187
L. Equations of Saturated Flow	188
Sample Problems	190

9. Flow of Water in Unsaturated Soil

A. Introduction	195
B. Comparison of Flow in Unsaturated versus Saturated Soil	195
C. Relation of Conductivity to Suction and Wetness	198
D. General Equation of Unsaturated Flow	202
E. Hydraulic Diffusivity	204
F. The Boltzmann Transformation	207
G. Theoretical Calculation of the Hydraulic Conductivity Function	209
H. Measurement of Unsaturated Hydraulic Conductivity and Diffusivity in the Laboratory	212
I. Measurement of Unsaturated Hydraulic Conductivity of Soil Profiles in Situ	213

J. Vapor Movement	221
Sample Problems	223

10. Movement of Solutes and Soil Salinity

A. Introduction	233
B. Convective Transport of Solutes	234
C. Diffusion of Solutes	236
D. Hydrodynamic Dispersion	238
E. Miscible Displacement and Breakthrough Curves	240
F. Combined Transport of Solutes	242
G. Effects of Solutes on Water Movement	245
H. Soil Salinity and Alkalinity	250
I. Salt Balance of the Soil Profile	251
J. Leaching of Excess Salts	254
Sample Problems	257

Part IV: THE GASEOUS PHASE

11. Soil Air and Aeration

A. Introduction	265
B. Volume Fraction of Soil Air	266
C. Composition of Soil Air	268
D. Convective Flow of Soil Air	269
E. Diffusion of Soil Air	272
F. Soil Respiration and Aeration Requirements	277
G. Measurement of Soil Aeration	280
Sample Problems	283

Part V: COMPOSITE PROPERTIES AND BEHAVIOR

12. Soil Temperature and Heat Flow

A. Introduction	287
B. Modes of Energy Transfer	288
C. Energy Balance for a Bare Soil	290
D. Conduction of Heat in Soil	291
E. Volumetric Heat Capacity of Soils	293
F. Thermal Conductivity of Soils	295
G. Simultaneous Transport of Heat and Moisture	300
H. Thermal Regime of Soil Profiles	303
I. Modification of the Soil Thermal Regime	309
Sample Problems	313

13. Stress–Strain Relations and Soil Strength

A. Introduction	318
B. The Concept of Strain and Stress	319
C. Elasticity and Plasticity	322
D. Rheology of Liquids	325
E. Rheological Models	327
F. Stress Distribution in Soil	328
G. The Mohr Circle of Stresses	331
H. Stress–Strain Relations and Failure of Soil Bodies	334
I. The Concept of Soil Strength	337
J. Measurement of Soil Strength	338
K. Soil Consistency	347
Sample Problems	352

14. Soil Compaction and Consolidation

A. Introduction	355
B. Two Opposing Views of Soil Compaction : Engineering and Agronomic	356
C. Soil Compactibility in Relation to Wetness	357
D. Occurrence of Soil Compaction in Agricultural Fields	360
E. Pressures Caused by Machinery	361
F. Soil Compaction under Machinery-Induced Stresses	367
G. Occurrence and Consequences of Soil Compaction	371
H. Control of Soil Compaction	375
I. Soil Consolidation	376
Sample Problems	382

Bibliography	387
---------------------	-----

INDEX	407
--------------	-----

This page intentionally left blank

“And furthermore, my son, be admonished
Of the making of many books there is no end
and much study is a weariness of the flesh.”

Ecclesiastes XII: 12

Preface

Tradition has it that wise King Solomon, using Ecclesiastes as *nom de plume*, reached his sorrowful conclusion (cited above) only in old age; otherwise, we might have been deprived of the enchanting “Song of Songs” of his youth and of the worldly “Proverbs” of his middle age.

This book is not, in any case, in total defiance of the Wise Old Man’s admonition, for it is not an entirely new book. Rather, it is an outgrowth of a previous treatise, written a decade ago, entitled “Soil and Water: Physical Principles and Processes.” Though that book was well enough received at the time, the passage of the years has inevitably made it necessary to either revise and update the same book, or to supplant it with a fresh approach in the form of a new book which might incorporate still-pertinent aspects of its predecessor without necessarily being limited to the older book’s format or point of view.

After some deliberation, I have decided to follow the second course. In so doing, I have also endeavored to enlarge the scope of the book so as to encompass a number of topics that were omitted or only scantily treated in the original book, such as the properties of clay, soil structure, soil aeration, soil heat, soil rheology and mechanics, and solute movement. Consequently, the present book is an attempt at a comprehensive, albeit elementary, exposition of the foundations of soil physics as a whole, rather than a restricted treatment of soil–water relations alone. A companion volume, entitled “Applications of Soil Physics,” deals specifically with the field- water cycle and associated phenomena.

In writing this book, I have attempted to answer the need for an upper-level undergraduate textbook in soil physics for students of the agricultural as well as of the environmental and engineering sciences. Toward this end, I

have made a conscious effort to avoid unnecessary technical or mathematical jargon and unfamiliar notation, and to explain each development explicitly without assuming anything more than general undergraduate knowledge of the basic concepts of calculus, physics, chemistry, and biology. This book is thus meant to be as autonomous and self-sustaining as possible. When necessary, however, the reader is referred to outside sources for supplementary study, particularly where the topic relates to a field of science outside the scope of our own necessarily limited coverage. Sample problems are presented at the end of each chapter and are worked out explicitly (in what some might consider *excruciating* detail) in an effort to help students transmute the vague abstractions of unfamiliar theory into actual working knowledge.

Some students of agriculture and biology are deterred by the very sight of mathematical equations, and tend to skip over them (as if they were merely irrelevant clusters of meaningless symbols . . .) and to read only the narrative text. This is a mistake. Equations should be deciphered and digested, for they provide essential information on the quantitative relationships among factors and variables, and they do so with precision and logic. Mathematics, as Josiah Willard Gibbs once defined it so aptly, is a *language*. In fact, it is the indispensable language of science. Ordinary language is too cumbersome and imprecise to replace the elegance and economy of mathematics. Still, the fear of mathematics is so pervasive that it alone can prevent highly intelligent people from understanding science. We have therefore attempted in this text to meet our friends half-way, by refraining from excessive or avoidable mathematical niceties and by going to some length to explain the mathematics we could not avoid.

Some students may even feel uneasy about the amount of physics involved in a study of soil physics. They, too, have nothing to fear. The concepts are elementary and ought to be understood by all naturalists. These concepts include the conservation of mass, energy, and momentum; velocity and acceleration; force and force fields; pressure and viscosity; as well as potential and kinetic energy. They also include a few basic physicochemical and thermodynamic concepts—all essential to the understanding not merely of soil physics but of all natural systems. At this point the bewildered student might be tempted to ask: Is that all? Well, that is *practically* all

A textbook on so vital a subject as soil physics ought by right to capture and convey the special fascination and excitement of the soil physicist's quest for knowledge and understanding of his (or her) complex system, and hence should give some pleasure in the reading. It is my hope that this book might be read, not merely consulted, and that the reader might discover in it a few insights as well as facts.

While any book written by an individual author inevitably reflects his particular point of view, it is in the nature of the ongoing process of scientific exchange that one's own ideas cannot easily be distinguished from those of numerous others. Some of the concepts elucidated herein have had their roots in my formal studies in various universities, mainly in my native U.S.A. Others were conceived during the course of my rather extensive travels, which included assignments and sojourns as observer, consultant, researcher, and teacher in such diverse places as Japan, India, Southeast Asia, Australia, Europe, Africa, and the Americas. An important nursery of this book is the State of Israel, where I witnessed and took part in the development of intensive land and water management methods which have enabled that country, despite its arid climate, to multiply its agricultural production severalfold within a single generation.

Being still in midcareer, I cannot yet assume the mantle of the Wise Old Man and encapsulate my experience as an ultimate truth in the form of a terse maxim of my own. Suffice it to say that I have already discovered the truth of the ancient Talmudic adage: "Much have I learned from my teachers, and yet more from my colleagues, but most of all from my students."

This page intentionally left blank

Acknowledgments

Thanks are due to the following colleagues who read and commented on various parts of the book during its formative stages: Professors John Baker, Allen Barker, Bernard Berger, Haim Gunner, and Mack Drake, as well as my graduate student David Leland, of the University of Massachusetts; and to Professors David Elrick of Guelph University and Peter Wierenga of New Mexico State University. I hereby absolve them of any responsibility for the book's undoubtedly numerous shortcomings, for which I alone am to blame. I am grateful to Lisa Cohn for her careful typing of the manuscript. Finally, an acknowledgment is also due to the draftsman who prepared the illustrations. Indeed he seemed to have worked harder on doing these than did the author on writing the text. However, being something of an amateur and still unsure of the quality of the results, he chooses to remain anonymous.

This page intentionally left blank

Part I:

BASIC RELATIONSHIPS

This page intentionally left blank

To see a world in a grain of sand
and heaven in a wild flower
Hold Infinity in the palm of your hand
and eternity in an hour.

William Blake
Innocence and Experience
1789–1794

1 *The Task of Soil Physics*

The soil beneath our feet is the basic substrate of all terrestrial life. The intricate and fertile mix composing the soil, with its special life-giving attributes, is a most intriguing field of study. The soil serves not only as a medium for plant growth and for microbiological activity per se but also as a sink and recycling factory for numerous waste products which might otherwise accumulate to poison our environment. Moreover, the soil supports our buildings and provides material for the construction of earthen structures such as dams and roadbeds.

The attempt to understand what constitutes the soil and how it operates within the overall biosphere, which is the essential task of soil science, derives both from the fundamental curiosity of man, which is his main creative impulse, and from urgent necessity. Soil and water are, after all, the two fundamental resources of our agriculture, as well as of our natural environment. The increasing pressure of population has made these resources scarce or has led to their abuse in many parts of the world. Indeed, the necessity to manage these resources efficiently on a sustained basis is one of the most vital tasks of our age.

That knowledge of the soil is imperative to ensure the future of civilization has been proven repeatedly in the past, at times disastrously. In many regions we find shocking examples of once-thriving agricultural fields reduced to desolation by man-induced erosion or salinization resulting from injudicious management of the soil–water system. Add to that the shortsighted depletion of unreplenished water resources as well as the dumping of poisonous wastes—and indeed we see a consistent pattern of mismanagement. In view of the population–environment–food crisis facing the world, we can ill afford to continue squandering and abusing such precious resources.