# **Soil Mechanics for Unsaturated Soils**

# D. G. Fredlund, Ph.D.

Professor of Civil Engineering University of Saskatchewan Saskatoon, Saskatchewan

# H. Rahardjo, Ph.D.

Senior Lecturer School of Civil and Structural Engineering Nanyang Technological University



A Wiley-Interscience Publication JOHN WILEY & SONS, INC. New York • Chichester • Brisbane • Toronto • Singapore This text is printed on acid-free paper.

Copyright © 1993 by John Wiley & Sons, Inc.

All rights reserved. Published simultaneously in Canada.

Reproduction or translation of any part of this work beyond that permitted by Section 107 or 108 of the 1976 United States Copyright Act without the permission of the copyright owner is unlawful. Requests for permission or further information should be addressed to the Permissions Department, John Wiley & Sons, Inc., 605 Third Avenue, New York, NY 10158-0012.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold with the understanding that the publisher is not engaged in rendering legal, accounting, or other professional services. If legal advice or other expert assistance is required, the services of a competent professional person should be sought.

#### Library of Congress Cataloging in Publication Data:

Fredlund, D. G. (Delwyn G.), 1940-Soil mechanics for unsaturated soils / D. G. Fredlund and H. Rahardjo
p. cm. Includes bibliographical references and index. ISBN 0-471-85008-X
1. Soil mechanics. 2. Soil moisture. 3. Soil—Testing.
I. Rahardjo, H. (Harianto) 11. Title. TA710.5.F73 1993
624.1'5136—dc20
92-30869

Printed in the United States of America

1098765432

#### Dedicated

## to our parents George and Esther Fredlund

### and

### Sugiarto and Pauline Rahardjo

who taught us that the fear of the Lord was the beginning of wisdom and that the love of the Lord makes life worth living

Delwyn G. Fredlund Harianto Rahardjo

# CONTENTS

CHAPTER 1	Introduction to Unsaturated Soil Mechanics	1
	1.1 Role of Climate	1
	1.2 Types of Problems	3
	1.2.1 Construction and Operation of a Dam	3
	1.2.2 Natural Slopes Subjected to Environmental Changes	5
	1.2.3 Mounding Below Waste Retention Ponds	6
	1.2.4 Stability of Vertical or Near Vertical Excavations	6
	1.2.5 Lateral Earth Pressures	7
	1.2.6 Bearing Capacity for Shallow Foundations	7
	1.2.7 Ground Movements Involving Expansive Soils	8
	1.2.8 Collapsing Soils	9
	1.2.9 Summary of Unsaturated Soils Examples	9
	1.3 Typical Profiles of Unsaturated Soils	9
	1.3.1 Typical Tropical Residual Soil Profile	10
	1.3.2 Typical Expansive Soils Profile	11
	1.4 Need for Unsaturated Soil Mechanics	12
	1.5 Scope of the Book	13
	1.6 Phases of an Unsaturated Soil	14
	1.6.1 Definition of a Phase	14
	1.6.2 Air-Water Interface or Contractile Skin	14
	1.7 Terminology and Definitions	15
	1.8 Historical Developments	16
		10
CHAPTER 2	Phase Properties and Relations	20
	2.1 Properties of the Individual Phases	20
	2.1.1 Density and Specific Volume	21
	Soil particles	21
	Water phase	21
	Air phase	21
	2.1.2 Viscosity	23
	2.1.3 Surface Tension	24
	2.2 Interaction of Air and Water	25
	2.2.1 Solid, Liquid, and Vapor States of Water	26
	2.2.2 Water Vapor	26
	2.2.3 Air Dissolving in Water	27
	Solubility of Air in Water	21
	Diffusion of Gases Through Water	2

tiv	CON	TENTS

	2.3 Volume-Mass Relations	29
	2.3.1 Porosity	29
	2.3.2 Void Ratio	30
	2.3.3 Degree of Saturation	30
	2.3.4 Water Content	31
	2.3.5 Soil Density	32
	2.3.6 Basic Volume-Mass Relationship	32
	2.3.7 Changes in Volume-Mass Properties	33
	2.3.8 Density of Mixtures Subjected to Compression of the Air Phase	34
	Piston-porous stone analogy	34
	Conservation of mass applied to a mixture	36
	Soil particles-water-air mixture	37
	Air-water mixture	37
CHAPTER 3	Stress State Variables	38
	3.1 History of the Description of the Stress State	38
	3.1.1 Effective Stress Concept for a Saturated Soil	38
	3.1.2 Proposed Effective Stress Equation for an Unsaturated Soil	39
	3.2 Stress State Variables for Unsaturated Soils	42
	3.2.1 Equilibrium Analysis for Unsaturated Soils	42
	Normal and shear stresses on a soil element	42
	Equilibrium equations	43
	3.2.2 Stress State Variables	43
	Other combinations of stress state variables	44
1	3.2.3 Saturated Soils as a Special Case of Unsaturated Soils	45
	3.2.4 Dry Soils	45
	3.3 Limiting Stress State Conditions	46
	3.4 Experimental Testing of the Stress State Variables	47
	3.4.1 The Concept of Axis Translation	47
	3.4.2 Null Tests to Test Stress State Variables	48
	3.4.3 Other Experimental Evidence in Support of the Proposed Stress State Variables	48
	3.5 Stress Analysis	49
	3.5.1 In Situ Stress State Component Profiles	49
	Coefficient of lateral earth pressure	52
	Matric suction profile	53
	Ground surface condition	53
	Environmental conditions	53
	Vegetation	53
	Water table	54
	Permeability of the soil profile	54
	3.5.2 Extended Mohr Diagram	54
	Equation of Mohr circles	55
	Construction of Mohr circles	56
	3.5.3 Stress Invariants	58
	3.5.4 Stress Points	58
	3.5.5 Stress Paths	
	3.6 Role of Osmotic Suction	59
		63

x

			CONTENT	s xv
CHAPTER 4	Mea	suremen	ts of Soil Suction	64
	4.1		of Soil Suction	64
			Components of Soil Suction	64
			Typical Suction Values and Their Measuring Devices	66
	4.2	Capillari	ty	67
		4.2.1	Capillary Height	67
		4.2.2	Capillary Pressure	68
		4.2.3	Height of Capillary Risc and Radius Effects	69
	4.3	Measure	ments of Total Suction	70
		4.3.1	Psychrometers	70
			Seebeck effects	70
			Peltier effects	70
			Peltier psychrometer	71
			Psychrometer calibration	73
			Psychrometer performance	74
		4.3.2	Filter paper	77
			Principle of measurement (filter paper method)	77
			Measurement and calibration techniques (filter paper method)	77
			The use of the filter paper method in practice	79
	4.4	Measure	ments of Matric Suction	80
		4.4.1	High Air Entry Disks	81
		4.4.2	Direct measurements	82
			Tensiometers	83
			Servicing the tensiometer prior to installation	84
			Servicing the tensiometer after installation	86
			Jet fill tensiometers	86
			Small tip tensiometer	86
			Quick Draw tensiometers	88
			Tensiometer performance for field measurements	88
			Osmotic tensiometers	90
			Axis-translation technique	91
		4.4.3	Indirect Measurements	93
			Thermal conductivity sensors	95
			Theory of operation	97
			Calibration of sensors	97
			Typical results of matric suction measurements	99
			The MCS 6000 sensors	99
			The AGWA-II sensors	100
	4.5		ments of Osmotic Suction	104
		4.5.1	Squeezing technique	105
CHAPTER 5	Flow	v Laws		107
	5.1	Flow of	Water	107
		5.1.1	Driving Potential for Water Phase	108
		5.1.2	Darcy's Law for Unsaturated Soils	110
		5.1.3	Coefficient of Permeability with Respect to the Water Phase	110
			Fluid and porous medium components	110

	Relationship	
	Relationship between permeability and volume- mass properties	111
	Effect of variations in degree of saturation on permeability	111
	Relationship between coefficient of permeability and degree of saturation	111
	Relationship between water coefficient of permeability and matric suction	113
	Relationship between water coefficient of permeability and volumetric water content	113
	Hysteresis of the permeability function	
	5.2 Flow of Air	116
	5.2.1 Driving Potential for Air Phase	117
	5.2.2 Fick's Law for Air Phase	117
	5.2.3 Coefficient of Permeability with Respect to Air Phase	117 119
	Relationship between air coefficient of permeability and degree of saturation	120
	Relationship between air coefficient of permeability and matric suction	120
	5.3 Diffusion	121
	5.3.1 Air Diffusion Through Water	121
	5.3.2 Chemical Diffusion Through Water	123
	5.4 Summary of Flow Laws	123
CHAPTER 6	Measurement of Permeability	124
	6.1 Measurement of Water Coefficient of Permeability	124
	6.1.1 Direct Methods to Measure Water Coefficient of Permeability	124
	Laboratory test methods	124
	Steady-state method	124
	Apparatus for steady-state method	125
	Computations using steady-state method	126
	Presentation of water coefficients of permeability	126
	Difficulties with the steady-state method	127
	Instantaneous profile method	127
	Instantaneous profile method proposed by Hamilton et al.	128
	Computations for the instantaneous profile method	129
	In situ field methods	130
	In situ instantaneous profile method	130
	Computations for the in situ instantaneous	131
	6.1.2 Indirect Methods to Compute Water Coemctent of Permeability	133
	Tempe pressure cell apparatus and test	135
	Volumetric pressure plate extractor apparates	135
	Test procedure for the volumetric pressure	136
	Drying portion of soil-water characteristic curve	

	CC	ONTENTS XVII
	Wetting portion of the soil-water characteristic curve	ic 136
	Computation of $k_w$ using the soil-water characteristic curve	136
	6.2 Measurement of Air Coefficient of Permeability	138
	Triaxial permeameter cell for the measuremen of air permeability	<i>ut</i> 140
	Triaxial permeameter cell for air and water permeability measurements	140
	6.3 Measurement of Diffusion	143
	6.3.1 Mechanism of Air Diffusion Through High Air Entry Disks	144
	6.3.2 Measurements of the Coefficient of Diffusion	144
	Procedure for computing diffusion properties	145
	6.3.3 Diffused Air Volume Indicators	146
	Bubble pump to measure diffused air volume	146
	Diffused air volume indicator (DAVI)	146
	Procedure for measuring diffused air volume	148
	Computation of diffused air volume	148
	Accuracy of the diffused air volume indicator	149
CHAPTER 7	Steady-State Flow	150
	7.1 Steady-State Water Flow	150
	7.1.1 Variation of Coefficient of Permeability with Space for an Unsaturated Soil	151
	Heterogeneous, isotropic steady-state seepag	e 151
	Heterogeneous, anisotropic steady-state seepage	151
	7.1.2 One-Dimensional Flow	152
	Formulation for one-dimensional flow	153
	Solution for one-dimensional flow	154
	Finite difference method	155
	Head boundary condition	155
	Flux boundary condition	156
	7.1.3 Two-Dimensional Flow	159
	Formulation for two-dimensional flow	159
	Solutions for two-dimensional flow	160
	Seepage analysis using the finite element method	161
	Examples of two-dimensional problems	164
	Infinite slope	171
	7.1.4 Three-Dimensional Flow	173
	7.2 Steady-State Air Flow	175
	7.2.1 One-Dimensional Flow	175
	7.2.2 Two-Dimensional Flow	176
	7.3 Steady-State Air Diffusion Through Water	177
CHAPTER 8	Pore Pressure Parameters	178
	8.1 Compressibility of Pore Fluids	178
	8.1.1 Air Compressibility	179
	8.1.2 Water Compressibility	179
	8.1.3 Compressibility of Air-Water Mixtures	179
	The use of pore pressure parameters in the compressibility equation	179

VIII CONTENT	S
--------------	---

	8.1.4	Components of Compressibility of an Air-Water Mixture	181
		Effects of free air on the compressibility of the mixture	182
		Effects of dissolved air on the compressibility of the mixture	182
	8.1.5	-	182
		Limitation of Kelvin's equation in formulating the compressibility equation	183
8.2	Derivati	ons of Pore Pressure Parameters	184
	8.2.1	Tangent and Secant Pore Pressure Parameters	185
	8.2.2	Summary of Necessary Constitutive Relations	186
	8.2.3	Drained and Undrained Loading	188
	8.2.4	Total Stress and Soil Anisotropy	190
	8.2.5	K <sub>0</sub> -Loading	191
	8.2.6	Hilf's Analysis	192
	8.2.7	Isotropic Loading	194
	8.2.8	Uniaxial Loading	196
	8.2.9	Triaxial Loading	196
	8.2.10	) Three-Dimensional Loading	199
	8.2.11	α Parameters	200
8.3		s of the Pore Pressure Equations and isons with Experimental Results	201
	8.3.1	Secant $B_h^*$ Pore Pressure Parameter Derived from Hilf's Analysis	201
	8.3.2	Graphical Procedure for Hilf's Analysis	202
	8.3.3	Experimental Results of Tangent B Pore Pressure Parameters for Isotropic Loading	204
	8.3.4	Theoretical Prediction of <i>B</i> Pore Pressure Parameters for Isotropic Loading	206
	8.3.5	Experimental Results of Tangent B and A Parameters for Triaxial Loading	215
	8.3.6	Experimental Measurements of the $\alpha$ Parameter	216
She	ar Streng	th Theory	217
9.1		of Shear Strength	217
	9.1.1	Data Associated with Incomplete Stress Variable Measurements	224
9.2	Failure E	Envelope for Unsaturated Soils	225
	9.2.1	Failure Criteria	225
	9.2.2	Shear Strength Equation	227
		Extended Mohr-Coulomb Failure Envelope	228
	9.2.4	Use of $(\sigma - u_w)$ and $(u_a - u_w)$ to Define Shear Strength	230
	9.2.5		231
9.3	Triaxial '	Tests on Unsaturated Soils	236
	9.3.1	Consolidated Drained Test	238
	9.3.2	Constant Water Content Test	238
	9.3.3	Consolidated Undrained Test with Pore Pressure Measurements	240
	9.3.4	Undrained Test	243
	9.3.5	Unconfined Compression Test	245

X

CHAPTER 9

CONTENTS	X1X

9.4 D	irect Shea	r Tests on Unsatured Soils	247
9.5 S	election of	f Strain Rate	248
	9.5.1 Ba	ackground on Strain Rates for Triaxial Testing	248
	9.5.2 St	rain Rates for Triaxial Tests	250
	9.5.3 D	isplacement Rate for Direct Shear Tests	254
9.6 M	fultistage	Testing	255
9.7 N	Ionlinearit	y of Failure Envelope	255
9.8 R	elationshi	ps Between $\phi^b$ and $\chi$	258
Measu	irement c	of Shear Strength Parameters	260
10.1	Special D	esign Considerations	260
	10.1.1	Axis-Translation Technique	260
	10.1.2	Pore-Water Pressure Control or Measurement	263
		Saturation procedure for a high air entry disk	266
	10.1.3	Pressure Response Below the Ceramic Disk	266
	10.1.4	Pore-Air Pressure Control or Measurement	272
	10.1.5	Water Volume Change Measurement	273
	10.1.6	Air Volume Change Measurement	275
	10.1.7	Overall Volume Change Measurement	275
	10.1.8	Specimen Preparation	276
	10.1.9	Backpressuring to Produce Saturation	277
10.2	Test Proc	edures for Triaxial Tests	279
	10.2.1	Consolidated Drained Test	280
	10.2.2	Constant Water Content Test	281
	10.2.3	Consolidated Undrained Test with Pore Pressure Measurements	281
	10.2.4	Undrained Test	282
	10.2.5	Unconfined Compression Test	282
10.3	Test Proc	edures for Direct Shear Tests	282
10.4	Typical T	est Results	284
	10.4.1	Triaxial Test Results	284
		Consolidated drained triaxial tests	284
		Constant water content triaxial tests	286
		Nonlinear shear strength versus matric suction	286
		Undrained and unconfined compression tests	288
	10.4.2	Direct Shear Test Results	289
Plastic	and Lin	nit Equilibrium	297
	Earth Pre		297
	11 1 1	At Rest Earth Pressure Conditions	298
	11.1.2	Estimation of Depth of Cracking	300
	11.1.2	Extended Rankine Theory of Earth Pressures	30
	11.1.5	Active earth pressure	30
		Coefficient of active earth pressure	30. 304
		Active earth pressure distribution (constant	30-
		matric suction with depth)	50-
		Tension zone depth	30
		Active earth pressure distribution (linear	30
		decrease in matric suction to the water table)	

### CHAPTER 10

CHAPTER 11

		Active earth pressure distribution when the soil has tension cracks	305
		Passive earth pressure	307
		Coefficient of passive earth pressure	307
		Passive earth pressure distribution (constant matric suction with depth)	307
		Passive earth pressure distribution (linear decrease in matric suction to the water table)	308
		Deformations with active and passive states	308
	11.1.4	Total Lateral Earth Force	309
		Active earth force	310
		Passive earth force	311
	11.1.5	Effect of Changes in Matric Suction on the Active and Passive Earth Pressure	312
		Relationship between swelling pressures and the earth pressures	313
	11.1.6	Unsupported Excavations	313
		Effect of tension cracks on the unsupported height	314
11.2	Bearing C	Capacity	315
	11.2.1	Terzaghi Bearing Capacity Theory	315
	11.2.2	Assessment of Shear Strength Parameters and a Design Matric Suction	317
		Stress state variable approach	317
		Total stress approach	318
	11.2.3	Bearing Capacity of Layered Systems	319
11.3	Slope Stal		320
11.5	11.3.1		
	11.3.1	Location of the Critical Slip Surface	320
	11.5.2	General Limit Equilibrium (GLE) Method	321
		Shear force mobilized equation	323
		Normal force equation	324
		Factor of safety with respect to moment equilibrium	324
		Factor of safety with respect to force equilibrium	325
		Interslice force function	325
		Procedures for solving the factors of safety equation	327
		Pore-water pressure designation	328
	11.3.3	Other Limit Equilibrium Methods	330
	11.3.4	Numerical Difficulties Associated with the Limit Equilibrium Method of Slices	332
	11.3.5	Effects of Negative Pore-Water Pressure on Slope Stability	333
		The "total cohesion" method	333
		Two examples using the ''total cohesion'' method	334
		Example no. 1	334
		Example no. 2	338
		The "extended shear strength" method	340
		General layout of problems and soil properties	340
		Initial conditions for the seepage analysis	342
		Seepage and slope stability results under high-intensity rainfall conditions	344

XX

CONTENTS	XXI

CHAPTER 12	Volu	346		
	12.1	Literature	Review	346
	12.2	Concepts	of Volume Change and Deformation	349
		12.2.1	Continuity Requirements	349
		12.2.2	Overall Volume Change	350
		12.2.3	Water and Air Volume Changes	351
	12.3	Constituti	ve Relations	351
		12.3.1	Elasticity Form	351
			Water phase constitutive relation	353
			Change in the volume of air	353
			Isotropic loading	354
			Uniaxial loading	354
			Triaxial loading	354
			K <sub>0</sub> -loading	356
			Plane strain loading	357
			Plane stress loading	357
		12.3.2	Compressibility Form	357
		12.3.3	Volume-Mass Form (Soil Mechanics Terminology)	358
		12.3.4	Use of $(\sigma - u_w)$ and $(u_a - u_w)$ to Formulate Constitutive Relations	358
	12.4	Experime Constituti	360	
		12.4.1	Sign Convention for Volumetric Deformation Properties	361
		12.4.2	Verification of Uniqueness of the Constitutive Surfaces Using Small Stress Changes	361
		12.4.3	Verification of the Constitutive Surfaces Using Large Stress State Variable Changes	363
	12.5	Relationship Among Volumetric Deformation Coefficients		365
		12.5.1	Relationship of Volumetric Deformation Coefficients for the Void Ratio and Water Content Surfaces	366
		12.5.2	Relationship of Volumetric Deformation Coefficients for the Volume-Mass Form of the Constitutive Surfaces	367
		12.5.3	Laboratory Tests Used for Obtaining Volumetric Deformation Coefficients	367
		12.5.4	Relationship of Volumetric Deformation Coefficients for Unloading Surfaces	369
		12.5.5	Relationship of Volumetric Deformation Coefficients for Loading and Unloading Surfaces	370
		12.5.6	Constitutive Surfaces on a Semi-Logarithmic Plot	370

CHAPTER 13	Measurements of Volume Change Indices	374
	13.1 Literature Review	374
	13.2 Test Procedures and Equipments	376
	13.2.1 Loading Constitutive Surfaces	377
	Oedometer tests	378
	Pressure plate drying tests	379
	Shrinkage tests	380

	Determination of volume change indices	380	
	Determination of volume change indices associated with the transition plane	382	
	Typical results from pressure plate tests	386	
	Determination of in situ stress state using oedometer test results	388	
	"Constant volume" test	388	
	"Free-swell" test	389	
	Correction for the compressibility of the apparatus	389	
	Correction for sampling disturbance	390	
	13.2.2 Unloading Constitutive Surfaces	392	
	Unloading tests after compression	392	
	Pressure plate wetting tests	393	
	Free-swell tests	394	
	Determination of volume change indices	395	
CHAPTER 14	Volume Change Predictions		
	14.1 Literature Review	397	
	14.1.1 Factors Affecting Total Heave	401	
	14.2 Past, Present, and Future States of Stress	403	
	14.2.1 Stress State History	404	
	14.2.2 In Situ Stress State	405	
	14.2.3 Future Stress State and Ground Movements	406	
	14.3 Theory of Heave Predictions	406	
	14.3.1 Total Heave Formulations	407	
	14.3.2 Prediction of Final Pore-Water Pressures	408	
	14.3.3 Example of Heave Calculations	408	
	14.3.4 Case Histories	410	
	Slab-on-grade floor, Regina, Saskatchewan	410	
	Eston school, Eston, Saskatchewan	411	
	14.4 Control Factors in Heave Prediction and Reduction	411	
	14.4.1 Closed-Form Heave Equation when Swelling Pressure is Constant	412	
	14.4.2 Effect of Correcting the Swelling Pressure on the Prediction of Total Heave	413	
	14.4.3 Example with Wetting from the Top to a Specified Depth	414	
	14.4.4 Example with a Portion of the Profile Removed by Excavation and Backfilled with a Nonexpansive Soil	415	
	14.5 Notes on Collapsible Soils	417	
CHAPTER 15	One-Dimensional Consolidation and Swelling		
	15.1 Literature Review		
	15.2 Physical Relations Required for the Formulation	419 420	
		422	
	15.3.1 Water Phase Partial Differential Equation	423	
	Saturated condition	424	
	Dry soil condition	424	
	Special case of an unsaturated soil condition	424	
	15.3.2 Air Phase Partial Differential Equation	425	
	Saturated soil condition	426	

			CONTENTS	xxiii
			Dry soil condition	426
			Special case of an unsaturated soil	426
	15.4		of Consolidation Equations Using Finite	427
	15.5		onsolidation Test Results for Unsaturated	429
		15.5.1	Tests on Compacted Kaolin	429
			Presentation of results	429
			Theoretical analyses	430
		15.5.2	Tests on Silty Sand	433
			Presentation of results	433
			Theoretical analysis	435
	15.6	Dimensio	nless Consolidation Parameters	437
CHAPTER 16		- and Thre sothermal	e-Dimensional Unsteady-State Flow and Analyses	440
	16.1	Uncouple	d Two-Dimensional Formulations	440
		16.1.1	Unsteady-State Seepage in Isotropic Soil	440
			Water phase partial differential equation	441
			Air phase partial differential equation	441
		16.1.2	Unsteady-State Seepage in an Anisotropic Soil	441
			Anisotropy in permeability	442
			Water phase partial differential equation	443
			Seepage analysis using the finite element method	444
			Examples of two-dimensional problems and their solutions	447
			Example of water flow through an earth dam	447
			Example of groundwater seepage below a lagoon	447
			Example of seepage within a layered hill slope	449
	16.2	Coupled I Consolida	Formulations of Three-Dimensional ation	456
		16.2.1	Constitutive Relations	456
			Soil structure	461
			Water phase	463
			Air phase	472
		16.2.2	Coupled Consolidation Equations	472
			Equilibrium equations	472
			Water phase continuity	473
			Air phase continuity	473
	16.3	Nonisothe	ermal Flow	473
		16.3.1	Air Phase Partial Differential Equation	47:
		16.3.2	Fluid and Vapor Flow Equation for the Water Phase	474
		16.3.3	Heat Flow Equation	474
		16.3.4	Atmospheric Boundary Conditions	47:
			Surface boundary conditions for air and fluid water flow	47:
			Surface boundary conditions for water vapor flow	47:
			Surface boundary conditions for heat flow	47

XXIV CONTENTS		
APPENDIX A	Units and Symbols	479
APPENDIX B	Theoretical Justification for Stress State Variables	483
	B.1 Equilibrium Equations for Unsaturated Soils	483
	B.2 Total or Overall Equilibrium	483
	B.3 Independent Phase Equilibrium	484
	B.3.1 Water Phase Equilibrium	485
	B.3.2 Air Phase Equilibrium	485
	B.3.3 Contractile Skin Equilibrium	485
	B.4 Equilibrium of the Soil Structure (i.e., Arrangement of Soil Particles)	488
	B.5 Other Combinations of Stress State Variables	489
	References	490
	About the Authors	508
	Index	510