

FOUNDATION ENGINEERING

Geotechnical
Principles
and Practical
Applications



Mc
Graw
Hill

RICHARD L. HANDY

Foundation Engineering

About the Author

Richard L. Handy is a Distinguished Professor Emeritus in the Department of Civil, Construction and Environmental Engineering at Iowa State University. A sought-after teacher, he served as the major professor for over 60 graduate students, many of whom have gone on to make major contributions in geotechnical engineering. A large number of former students and associates recently collaborated to endow a Professorship in his name, and a book of collected papers was issued in his honor.

Dr. Handy may be best known as the inventor of Borehole Shear Tests that perform in-situ measurements of cohesion and friction in soils and rocks. The soil test was used in snow when he and six engineering students were conducting research on an epic voyage of a large ship in the ice-bound Northwest Passage. They also observed the catenary shape of an igloo, which he later adapted to solve a problem that had intrigued Terzaghi, to mathematically define arching action in soils. The analysis revealed that conventional analyses are on the unsafe side and explained a wall failure where there were four fatalities. It received the Thomas A. Middlebrooks Award of the American Society of Civil Engineers.

Dr. Handy also was active in geology. He proposed a variable-wind hypothesis to explain the distribution of wind-blown silt (loess), and showed that the rate of growth of a river meander slows down in time according to a *first-order rate equation*. He then applied the same equation to rates of primary and secondary consolidation in engineering. In recognition of his contributions to geology he was elected a Fellow in the Geological Society of America and the American Association for the Advancement of Science.

Known for his sense of humor, Dr. Handy liked to point out that it is better to have a joke that turns out to be an invention than an invention that turns out to be a joke. His *The Day the House Fell*, published by the American Society of Civil Engineers, Reston, VA, for non-engineers, became a best-seller. His book *FORE and the Future of Practically Everything* published by Moonshine Cove Publishing, Abbeville, SC, adapts first-order rate equations to practically everything, including track world records and baseball home runs.

Dr. Handy also founded and is the Past President of a company that bears his name. The company manufactures and sells geotechnical instruments, with emphasis on in-situ test methods that were created and developed under his direction.

Foundation Engineering

Geotechnical Principles and Practical Applications

By Richard L. Handy, Ph.D.
*Distinguished Professor Emeritus
Iowa State University*



New York Chicago San Francisco
Athens London Madrid
Mexico City Milan New Delhi
Singapore Sydney Toronto

Copyright © 2020 by McGraw-Hill Education. All rights reserved. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a database or retrieval system, without the prior written permission of the publisher.

ISBN: 978-1-26-002604-7

MHID: 1-26-002604-3

The material in this eBook also appears in the print version of this title: ISBN: 978-1-26-002603-0,

MHID: 1-26-002603-5.

eBook conversion by codeMantra

Version 1.0

All trademarks are trademarks of their respective owners. Rather than put a trademark symbol after every occurrence of a trademarked name, we use names in an editorial fashion only, and to the benefit of the trademark owner, with no intention of infringement of the trademark. Where such designations appear in this book, they have been printed with initial caps.

McGraw-Hill Education eBooks are available at special quantity discounts to use as premiums and sales promotions or for use in corporate training programs. To contact a representative, please visit the Contact Us page at www.mhprofessional.com.

Information contained in this work has been obtained by McGraw-Hill Education from sources believed to be reliable. However, neither McGraw-Hill Education nor its authors guarantee the accuracy or completeness of any information published herein, and neither McGraw-Hill Education nor its authors shall be responsible for any errors, omissions, or damages arising out of use of this information. This work is published with the understanding that McGraw-Hill Education and its authors are supplying information but are not attempting to render engineering or other professional services. If such services are required, the assistance of an appropriate professional should be sought.

TERMS OF USE

This is a copyrighted work and McGraw-Hill Education and its licensors reserve all rights in and to the work. Use of this work is subject to these terms. Except as permitted under the Copyright Act of 1976 and the right to store and retrieve one copy of the work, you may not decompile, disassemble, reverse engineer, reproduce, modify, create derivative works based upon, transmit, distribute, disseminate, sell, publish or sublicense the work or any part of it without McGraw-Hill Education's prior consent. You may use the work for your own noncommercial and personal use; any other use of the work is strictly prohibited. Your right to use the work may be terminated if you fail to comply with these terms.

THE WORK IS PROVIDED "AS IS." McGRAW-HILL EDUCATION AND ITS LICENSORS MAKE NO GUARANTEES OR WARRANTIES AS TO THE ACCURACY, ADEQUACY OR COMPLETENESS OF OR RESULTS TO BE OBTAINED FROM USING THE WORK, INCLUDING ANY INFORMATION THAT CAN BE ACCESSED THROUGH THE WORK VIA HYPERLINK OR OTHERWISE, AND EXPRESSLY DISCLAIM ANY WARRANTY, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO IMPLIED WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. McGraw-Hill Education and its licensors do not warrant or guarantee that the functions contained in the work will meet your requirements or that its operation will be uninterrupted or error free. Neither McGraw-Hill Education nor its licensors shall be liable to you or anyone else for any inaccuracy, error or omission, regardless of cause, in the work or for any damages resulting therefrom. McGraw-Hill Education has no responsibility for the content of any information accessed through the work. Under no circumstances shall McGraw-Hill Education and/or its licensors be liable for any indirect, incidental, special, punitive, consequential or similar damages that result from the use of or inability to use the work, even if any of them has been advised of the possibility of such damages. This limitation of liability shall apply to any claim or cause whatsoever whether such claim or cause arises in contract, tort or otherwise.

Contents

Preface	xv
Introduction	xvii
1 Defining What Is There	1
1.1 The Three Most Common Construction Materials	1
1.2 Two Classes of Foundations	2
Support of Deep Foundations	2
Expansive Clays Can Be Expensive Clays	2
End Bearing on Rock	2
Ground Improvement	3
1.3 Residual Soils	3
Travel Is Wearing	3
1.4 Soil Layers Created by Weathering	4
Topsoil “A Horizon”	4
Subsoil “B Horizon”	5
Shrinkage Cracks and Blocky Structure in Expansive Clays	5
1.5 Vertical Mixing in Expansive Clay	6
1.6 Influence from a Groundwater Table (or Tables)	6
Groundwater Table and Soil Color	6
A Perched Groundwater Table	6
1.7 Intermittent Recycling	7
1.8 Soil Types and Foundations	7
Influence of a Groundwater Table	8
Pull-up of Deep Foundations by Expansive Clay	9
1.9 Agricultural Soil Maps	9
The Soil Series	9
1.10 Distinguishing between Alluvial Soils	9
Rivers and Continental Glaciation	10
Meanders and Cutoffs	10
Oxbow Lake Clay	11
Alluvial Fans	12
Natural Levees	12
Slack-Water (Backswamp) Floodplain Deposits	12
Air Photo Interpretation	12
1.11 Wind-Deposited Soils	13
Sand Dunes	13
Eolian Silt Deposits	13
1.12 Landslides	14
Landslide Scarps	14
A No-No! Landslide Repair Method	15
When Landslides Stop	16

	Recognizing Landslides	16
	Not a Good Place for a Patio	16
1.13	Stopping a Landslide	16
	Drainage	16
	Structural Restraints: Piles, Stone Columns, and Retaining Walls	17
	Chemical Stabilization	17
	Drilled Quicklime	17
1.14	Rock That Isn't There	18
	Near-Surface Features	18
	Shallow Caverns and Sinks	19
	Locating Underground Caverns	20
	Abandoned Mine Shafts and Tunnels	20
	Tunneling Machines and the Rock That Isn't There	20
1.15	The Big Picture	21
	Mountain Ranges, Volcanoes, and Earthquakes	21
	Soil Responses to Earthquakes	21
	Earthquake Recurrence Intervals	22
1.16	The Walkabout	23
	Problems	23
	Further Reading	24
2	Getting along with Classification	25
2.1	A Hands-On Experience	25
2.2	An Engineered Soil Moisture Content	25
2.3	Standardizing the Plastic Limit Test	26
	The Plastic Limit in Engineering	26
2.4	Going from Plastic and Remoldable to Liquid and Flowable	27
	Standardizing the LL Test	27
	The Fall Cone Test	27
2.5	The Plasticity Index	28
2.6	Atterberg Limits in Soil Classification	29
2.7	WWII and New Rules for Soil Classification	30
2.8	Atterberg Limits and Criteria for Expansion	31
2.9	Kinds of Clay Minerals	31
	A Layered Crystal Structure	31
	An Expansive Crystal Structure	32
	Going Tribal	34
	When Sodium, Na ⁺ , Replaces Calcium, Ca ⁺⁺	34
	Drilling Mud	34
2.10	A Hands-On Test for Expansive Clay	34
	Field Test	34
2.11	Some Clues to Expansive Clay	34
2.12	Measuring Soil Particle Sizes	35
	Statistical Interpretation	35
	Defining Clay Size	36

2.13	Particle Sizes Determined from Sedimentation Rates in Water . . .	36
	Performing a Sedimentation Test	36
	Defining Clay Size	38
2.14	Some Soil Characteristics Related to Grain Size	
	Distribution Curves	38
2.15	Defining Size Grades	38
	Gravel/Sand	38
	Sand/Silt	38
	Clay and Silt	39
	Expansive versus Non-expansive Clay	39
	Salt versus Fresh Water Clay Deposits	39
	Problems.	39
	Further Reading	40
3	Foundation Settlement	41
3.1	Castles and Cathedrals.	41
	Cathedrals	41
3.2	A Scientific Approach to Foundation Settlement	41
	The Test.	42
	A Eureka Moment!	42
3.3	Influence of Time.	43
3.4	Amount of Settlement	45
	Void Ratio and Settlement	45
	Calculating a Void Ratio	45
3.5	Overconsolidation and the Compression Index	46
3.6	Consolidation Rate	46
	Defining a Drainage Distance	48
3.7	Pore Water Pressure and Foundation Bearing Capacity	48
	Field Monitoring.	48
3.8	Pore Water Pressure Dissipation and Rate of Primary Consolidation	48
3.9	Evaluating C_v	49
3.10	A Reference Time for 90 Percent Primary Consolidation	50
3.11	It's Not Over Until It's Over: Secondary Consolidation	50
3.12	First-Order Rate Equations	50
3.13	Field Time for Secondary Consolidation	51
	Field Data	52
3.14	Defining a Preconsolidation Pressure	52
	Casagrande Method	53
	Correcting for Sample Disturbance	53
	Use and Misuse of OCR	54
3.15	Lambe's Stress Path Approach to Settlement	54
3.16	Differential Settlement.	55
	Problems with Building Additions	55
3.17	The Other Shoe	56
	Problems.	56

	References	57
	Further Reading	57
4	Soils Behaving Badly	59
4.1	Expansive Clays	59
	Expansive Clay in a Consolidation Test	59
4.2	Two Classes of Expansive Clays	60
	Type G Clays	60
	Type P Clays	60
	How a Layer of Expansive Clay Can Cause Trouble	60
	Nature's Color Coding	60
4.3	Sorting Out Floodplain Clays	61
	What Makes River Floodplains Wide	61
	Braided Rivers	61
	Meandering Rivers	61
	A Shift from Braided to Meandering	61
4.4	Floodplain Soils of Meandering Rivers	62
	Oxbow Lake Clay	62
	Depth and Shape of an Oxbow	62
	Slack-Water or Backswamp Deposits	62
4.5	Deep Tropical Weathering and Expansive Clay	63
4.6	A Guide to Expansive Clay	63
	Crystal Structure in Control	63
4.7	Field Evidence for Expansive Clay	64
	More Bad Karma	64
4.8	Managing Expansive Clay	65
	The Chainsaw Method	65
	Structural Slabs, Grade Beams, and Piles	65
	Stripping off the Active Layer	65
	Observations of Strange Field Behavior	67
4.9	The Replacement Method	67
	How Does It Work?	67
	New Rule for Control of Expansive Clay	68
	Clues to Between-Layer Stacking of Water Molecules	68
	Hypothesis	69
	Why Does Clay Expansion Stop at 3 Layers?	69
	What's in a Name?	69
4.10	Chemical Stabilization of Expansive Clay with Lime	69
4.11	<i>Collapsible</i> Soils	70
	Delayed Collapse	70
	Collapsible Alluvium	71
4.12	Regional Changes in Properties of Wind-Deposited Soils	71
4.13	Quick Clays!	72
	Vane Shear Does Not Just Measure Soil Cohesion	72
4.14	Liquefaction!	73
	Identifying Vulnerable Soils	73

	Earthquakes, Volcanoes, and the “Ring of Fire”	73
	Made Earthquakes	74
4.15	Pretreatment to Prevent Liquefaction	74
4.16	Earthquake Dynamics	75
	Recurrence Intervals.....	75
4.17	Quicksand	76
4.18	Blessed Are the Computers But Will They Really Inherit the Earth?	76
	Problems.....	76
	References	77
5	Stresses in Soils	79
5.1	Concentrated Stresses.....	79
5.2	Adapting Boussinesq Theory	80
5.3	A Snag in the Relationship	81
5.4	Approximating the Pressure Distributions.....	81
5.5	Preloading	82
5.6	A Plate Bearing Test as a Model Foundation	84
5.7	Performing a Plate Bearing Test	85
5.8	The Progressive Nature of a Bearing Capacity Failure.....	86
5.9	Plate Bearing Tests on Weathered Soil Profiles.....	86
5.10	Foundation Stresses Transferred to Nearby Unyielding Walls....	88
5.11	Strength Gains from Aging	89
	Interruptions during Pile Driving	90
5.12	A Convenient Maximum Depth for Pressure Calculations	90
	Problems.....	90
	References	91
6	Evaluating Soil Shear Strength.....	93
6.1	Bearing Capacity and Settlement	93
6.2	Friction	93
	Friction Angle and Slope Angle	94
	Amontons’ Second Law.....	94
	The Greek Connection	95
	Coulomb’s Equation.....	95
6.3	Friction Angle in Soils	96
	Dilatancy in Design	96
6.4	A Direct Shear Test	96
	Influence of Layering.....	97
	The Borehole Shear Test (BST)	98
6.5	Unconfined Compression Test	100
6.6	Mohr’s Theory	100
	Pore Water Pressure	102
6.7	A Difficult Problem.....	102
	Stage Testing	103
	Lambe’s Stress Path Method.....	103
	What about the Intermediate Principal Stress?	103

6.8	Statistical Analysis of Test Data	104
	R^2 (R squared)	104
	Triaxial Shear Tests	104
	Problems.	104
	References	105
	Further Reading	105
7	Shallow Foundation Bearing Capacity	107
7.1	Bearing Capacity versus Settlement.	107
	Temporary Excess Pore Water Pressure.	107
	Unanticipated Loading	107
7.2	Fair Warning	108
	Two Kinds of Decrease in Pore Water Pressure	108
	Drainage.	108
	Sensitive Soils	108
7.3	Foundations on Compacted Soil Fill	108
	Procedure and Performance Tests	109
	Cut-and-Fill	109
7.4	Bearing Capacity Equations	109
	Equation Development	109
7.5	Prandtl-Terzaghi Analysis	110
	Rough Base, Smooth Base	112
	Meyerhof's Modification	112
7.6	Terzaghi Bearing Capacity Factors.	112
	Local Shear.	115
	Alternative Solutions	115
7.7	What Is the <i>Real</i> Factor of Safety?	115
7.8	Bearing Capacity in 3D	116
7.9	Eccentric Loading	117
	Foundations for Retaining Walls	117
7.10	Mine Collapse	119
	Shallow Mines.	119
	Deep Mines	119
	Dangers of Vertical Mineshafts.	119
	Longwall Mining	119
7.11	A Natural History of Caverns	120
7.12	Frost Heave and Footing Depth	120
	Arctic Permafrost	121
	Polygonal Ground.	121
	Elongated Lakes	121
	Some Practical Consequences.	121
	Methane Release	121
7.13	When Things Go Wrong	122
	Problems	123
	References	123
	Further Reading	123

8	The Standard Penetration Test in Foundation Engineering	125
8.1	The Empirical Approach	125
8.2	Soil Penetration Tests	125
	Selective Test Depths	127
	Groundwater	127
	Sample Disturbance	127
	The “Pocket Penetrometer”	128
	Shelby Tube Samples	128
8.3	SPT in Sand	128
	Depth Correction.	128
	A General Depth Correction	129
8.4	Soil Mechanics of the SPT	130
	What Might Be Achieved by Subtracting Blow Counts?	130
8.5	The SPT Hammers’ Biggest Hits	130
	Adjusting the <i>N</i> Value	130
8.6	SPT “ <i>N</i> ” Values and Settlement of Foundations on Sand.	132
	A Shallow Depth Correction	132
8.7	Pressure Bulb Correction	133
8.8	Bearing Capacity of Sand Based on an Estimated Friction Angle	135
8.9	Comparisons with Measured Settlements	135
8.10	Foundation Bearing Capacities on Clay Based on SPT or Unconfined Compressive Strength	136
	Theoretical Foundation Design on Clay Based on Unconfined Compressive Strength	137
	Net Bearing Pressure	137
	Reducing Settlement with a Mat Foundation.	137
	Summary	138
	Problems	138
	References	139
	Further Reading	139
9	Probing with Cone Penetration Tests and the Marchetti Dilatometer	141
9.1	A Classical Approach	141
9.2	Pushing versus Driving	142
9.3	A “Friction Ratio”	142
9.4	Mechanical versus Electrical Cones	143
	The Piezocone	144
	Decision Time: What Are Advantages/Disadvantages of Cone and SPT?	145
	Advantages and Disadvantages of Cone Tests.	145
	Piezocone and Groundwater Table	145
9.5	Fracking (Hydraulic Fracturing)	145
9.6	Example of Cone Test Data	146

9.7	Normalizing Cone Test Data for Test Depth.....	147
	Dealing with Dimensions	147
9.8	Cone Test Data and Settlement of Foundations on Sand	148
9.9	Cone Tests and Foundations on Saturated, Compressible Clay.....	148
9.10	Precaution with Empirical Relationships	149
9.11	Time-outs for Pore Pressure Dissipation.....	149
9.12	Supplemental Cone Test Data.....	149
9.13	The Marchetti Dilatometer	150
	Preparation for Testing.....	151
	Soil Identifications	152
9.14	Predicting Settlement.....	152
9.15	A Key Question: How Can Lateral Yielding Predict Vertical Settlement?.....	153
	Aging	153
	A Dilatometer Shift in Direction of the Major Principal Stress....	154
	Problems.....	154
	References	155
	Further Reading	155
10	Focus on Lateral Stress	157
10.1	Lower Cost, More Convenient	157
10.2	The Pressuremeter	157
	Soil Disturbance from Drilling	157
	Self-Boring Pressuremeters	158
10.3	Interpretation of Pressuremeter Test Data	159
	Lateral In Situ Stress.....	159
	The Limit Pressure in Foundation Engineering.....	159
	A Theoretical Approach.....	160
	Use in Design	161
	Soil Identifications	161
10.4	The K_0 Stepped Blade.....	161
	The Two-Chambered Pressure Cell	162
	Test Sequence	163
	Interpretation	163
	Example	163
10.5	Summary	164
	Problems.....	165
	References	165
11	Design of Deep Foundations	167
11.1	Transferring a Foundation Load Deep to Reduce Settlement	167
11.2	When Pile Foundations Became a Matter of Necessity.....	167
11.3	Soils and City Planning	167
	Cities and Rivers.....	168
11.4	Lowering of Sea Level	168
11.5	End Bearing	169
11.6	Pile Driving	169
	Wood Piles	169

	The Science of Hammering	169
	Hard Driving and Brooming of Wood Piles	170
	No Lunch Breaks!	170
11.7	Tension Breaks in Concrete Piles Caused by Pile Driving?	170
	Piles Doing a U-turn.	170
11.8	The Engineering News Formula.	170
11.9	Pile Bearing Capacities and Load Tests	171
	Strength Gains and Slow Loading	171
	Anchor Requirements	171
	Conduct of a Test.	172
	Criteria for Failure	172
	Marginal Designs	172
11.10	Analyzing Hammer Blows	173
	A Wave Equation for Driven Piles	173
	A Pile Driving Analyzer (PDA).	173
	Measuring Setup with PDA and Restrike	174
11.11	Citizen Complaints.	175
11.12	Pile Load Capacities: End Bearing	175
	End Bearing on Rock	175
	Rock Quality	176
	Rock Sockets	176
	End Bearing on Sand	176
	A Critical Depth for End Bearing	178
11.13	Skin Friction and Adhesion.	178
	Depth and Differential Movement.	178
	Negative Skin Friction (Adhesion).	179
	End Bearing and Skin “Friction”	179
	Uplift from Expansive Clay.	179
11.14	Drilled Shaft Foundations	180
	A Bad Scene	180
	Slow Demise of the Belled Caisson	180
11.15	Saving Time and Money on Load Tests with the Osterberg Cell.	180
	Representative Test Results.	180
	Comparisons with Top-Down Load Tests	181
11.16	Franki Piles	182
11.17	Augercast Piles	182
	Jet-Grouted Micropiles.	184
11.18	Common Piles Materials	184
	Definitions of a Factor of Safety	184
11.19	Preliminary Estimates for Deep Foundation Bearing Capacity.	184
11.20	Pile Group Action	188
	Pile Separation Distances.	189
	Pile Group Action Formulas	189
	Batter Piles	190

	Questions	190
	References	191
	Further Reading	191
12	Ground Improvement.	193
12.1	What Is Ground Improvement?	193
12.2	Preloading	193
	Enhancing and Monitoring the Rate of Settlement	193
	A Complex System	194
12.3	Compaction	194
	Vibratory Compaction	194
	Deep Dynamic Compaction (DDC)	194
	Blasting.	195
	Side Effects from Compaction.	195
12.4	Soil Replacement or Improvement.	195
	Stone Columns, Aggregate, and Mixed-in-Place Piers	195
12.5	Grout Materials	197
12.6	Grout “Take”	197
12.7	Rammed Aggregate Piers	197
	A “Saw-Tooth” Stress Pattern	199
	Temporary Liquefaction.	199
	Tension Cracks Outside the Liquefied Zone.	199
12.8	A Hypothesis of Friction Reversal	200
	Conditioning	201
	Friction Reversal and Overconsolidation	201
12.9	Advanced Course: Application of Mohr’s Theory	201
	Lateral Stress and Settlement	202
	Is Excavation Permitted Close to RAPS?	203
12.10	Further Developments	203
	RAPS as Anchor Piers	203
	When Soil Does Not Hold an Open Boring	203
	Low-Slump Concrete Piers	203
	Sand Piers.	203
	Questions	203
	Reference	204
	Appendix: The Engineering Report and Legal Issues	205
	Index.	207

Preface

The thread of learning is strengthened through understanding.

Soil is the most abundant construction material, and also the most variable. Early engineering tests of soils involved the resistance to jabbing with a heel or probing with a stick. Probing then developed along two different approaches, hammering and pushing. Both can provide useful information, but the tests do not accurately simulate soil behavior under or near a foundation.

Targeted Tests

A targeted test is one that is directly applicable for design. An example is a pile load test that relates settlement to the applied load. A load test also can be continued to determine an ultimate bearing capacity. A *plate bearing test* can similarly model a shallow foundation, but scaling down makes the results less directly applicable.

A third approach is to obtain and preserve soil samples in their natural state and test them in a laboratory. The problem then becomes how to collect a soil sample without disturbing it, as even the removal of a confining pressure can effect a change.

An Early Targeted Test

The laboratory consolidation test devised by Karl Terzaghi was targeted to measure soil behavior as it may influence foundation settlement. Observations and measurements made during the tests then led to an important spinoff, the concept that pore water pressure subtracts from normal stress and therefore from friction. That now is considered by many to be the entry point for modern soil mechanics.

A Simple Targeted Test

The plastic limit test must be one of the simplest soil tests ever devised, and results are part of most engineering soil classifications. The test uses hand power to roll out, bunch up, and re-roll threads of soil until it dries out and crumbles. The transition moisture content is the plastic limit. It not only depends on a soil clay content but also on its clay mineralogy, and the test was devised long before it became recognized that there is a clay mineralogy.

Two Requirements in Foundation Design

Requirements are as follows: (1) Settlement must be uniform and must not be excessive, and (2) a foundation must not punch down into the ground in a *bearing capacity* failure. If a near-surface soil is not adequate, deep foundations can transfer loads downward to bear on rock or in more competent soil. A complication for deep foundations is that they can derive support from two sources, end-bearing and side friction, and the two contributions are not separated with ordinary top-load tests. They can be isolated by using an expandable *Osterberg cell* to push up from the bottom. Pile behavior and integrity also can be examined with impacts and sound waves.

A New Role for Lateral Soil Pressure

Laboratory triaxial shear tests define relationships between lateral confining pressure and soil strength and bearing capacity. Field tests have led to the discovery that a high lateral pressure imposed on saturated soil can work a temporary change in the soil behavior, and the change can be an important factor affecting foundation settlement. That development is given special attention in the last chapter of this book.

Soil Origins and Clay Mineralogy

One mistake is one too many, but mistakes happen. In foundation engineering a mistake sometimes can be attributed to a disconnect between engineering purpose and site geology. Most soil is hidden away, and geology and soil science, which emphasizes changes caused by weathering, can reveal where and what to look for. For example, expansive clays that cause no end of engineering problems are far more common than can be shown on small-scale engineering soil maps. The geotechnical engineer who is not cognizant of geological relationships and engineering consequences is riding on one wheel.

The Engineer as Teacher

Case history. An architect designed a building with exterior walls of Italian marble, and was in no mood to spend money for deep foundations or anything else that “would not show.” He had to be convinced that without deep foundations, the consequences would show.

Introduction

Some Heroes in Geotechnical/Foundation Engineering

Archimedes (287–212 BC) famously discovered “Archimedes Principle” of buoyancy, which affects soil weight and frictional resistance to sliding. He was killed by a Roman soldier who had no appreciation.

Charles-Augustin de Coulomb (1736–1806) was a French military engineer, and while being in charge of building a fort on the island of Martinique he observed that sand grains must have friction or they would not make a respectable pile. He also reasoned that clay must have cohesion or it would not stand unsupported in a steep bank. Those observations led to the “Coulomb equation” for soil shear strength. Over 100 years later, Karl Terzaghi added the influence from pore water pressure that tends to push grains apart.

Coulomb also derived an equation for the lateral force from soil pushing against a retaining wall. The equation, and a later equation proposed by Rankine, puts the maximum soil pressure at the base of a wall but tests conducted by Terzaghi indicate that it is more likely to be zero. That is no small error because raising the height of the center of pressure increases the overturning moment, which makes the Coulomb and Rankine solutions the unsafe side.

Coulomb's Law

After retiring from the Army, Coulomb entered a contest to invent a better marine compass. He did not win the contest but invented the torsion balance that substitutes twisting of fine wires for knife edges. Coulomb then experimented with his instrument to measure tiny forces from electrical charges, electricity being big at the time, and discovered that forces between two electrically charged particles depend on *square* of the separation distance. Coulomb's Law also governs space travel and orbiting distances of satellites.

William John Macquorn Rankine (1820–1872) was a professor at the University of Glasgow. He was most famous for his analysis of the thermodynamics of steam engines, but he also had a simple solution for soil pressures against retaining walls. He defined an *active state* for soil that is acting to retain itself, and a *passive state* for soil that is being pushed. Rankine's and Coulomb's analyses can give the same answers, but both have a limitation.

Christian Otto Mohr (1835–1918) was a German bridge engineer and a professor of mechanics at Stuttgart and Dresden. He devised the “Mohr circle” graphical method

for depicting soil stresses, and the “Mohr envelope” defines stress conditions for shear failure. It supports Coulomb’s soil shear strength equation.

Ludwig Prandtl (1875–1953) was a professor at the University of Hanover, most famous for his contributions to aerodynamics. He also developed a theory for the resistance of metal to penetration by a punch based on a curved failure surface called a *log spiral*.

Karl Terzaghi (1883–1963) was from Austria and was educated in mechanical engineering. However, he also was interested in geology and became a professional geologist. He then used an engineering approach for soil problems, for example, by applying Prandtl’s *log spiral* to shallow foundation bearing capacity, a theory and approach that still are widely used. As a professor at Robert College in Turkey, Terzaghi devised the consolidation test and theory for predicting foundation settlement. Those observations led to defining soil shear strength in terms of *effective stress* that takes into account the influence from excess pore water pressure.

Terzaghi also observed that because clay particles must be soft and yielding, contact areas between particles can be expected to vary depending on the contact pressure, which might explain the linear relationship between friction and normal stress. It is the concept that made its way back into mechanical engineering to explain friction. It also can explain the function of a lubricant, to keep surfaces separated.

Geotechnical engineering has grown and continues to grow, and many investigators and practitioners continue to make important contributions. Broad interests, curiosity, imagination, and an interest in working with a complex and somewhat unpredictable natural material are part of the toolkit.

Further Reading

Bowden, F. P., and Tabor, D., *The Friction and Lubrication of Solids*, Oxford University Press, Oxford, UK, 1950.

Casagrande, A., “Karl Terzaghi—His Life and Achievements,” In *From Theory to Practice in Soil Mechanics*, L. Bjerrum, A. Casagrande, R. B. Peck, and A. W. Skempton, eds. John Wiley & Sons, New York, 1960.

Handy, R. L., “The Arch in Soil Arching,” *ASCE Journal of the Geotechnical Engineering Division*, 111(GT3):302–318, 1985.

Terzaghi, K., *Theoretical Soil Mechanics*, John Wiley and Sons, Inc., New York, 1943.



Karl Terzaghi (1883–1963). Pencil sketch by Tauseef Choudry.

This page intentionally left blank

CHAPTER 1

Defining What Is There

Geology and Foundation Engineering

1.1. The Three Most Common Construction Materials

Concrete has a recipe, steel is made to order and goes by number, and soil and rock are what is there. A first requirement in foundation engineering therefore is to determine and characterize what is there. That requires knowledge or at least familiarity with site geology.

For example, soils of river floodplains are likely to occur as sedimentary layers. A common sequence is clay layers on top of sand layers on top of gravel, as flow velocities decreased during stages of deposition. Soils deposited by winds are more likely to transition horizontally, from sand dunes adjacent to a source to thick, highly erodible deposits of silt that has such an open structure that when saturated with water can collapse under its own weight. With increasing distance from a source the silt is transitional to clay that is particularly troublesome because it is expansive and can lift building foundations in the presence of water.

Procedures used for identifying, boring, probing, sampling, and/or testing vary with different kinds of deposits because of the variability and focus on particular engineering properties. Core samples obtained by pushing a steel tube into the soil are commonly called “undisturbed,” but the term is shielded by optimism. A soil that is relieved of existing pressure will respond by simply expanding, so it, to some degree, is disturbed. It also is not possible to accurately reproduce field conditions in a laboratory if, as often is the case, those conditions are not known and are difficult to measure. Many important engineering soil properties are inherited, for example, from having been buried under a thousand meters of glacial ice or a hundred meters or more of soil that has been removed by erosion.

Soils usually are investigated with borings, but there can be no guarantee of what engineering perils may exist between the borings. This limitation is included in every geotechnical report, and usually is written with the assistance of an attorney. Geological awareness can help to make sense out of a situation and can be critical.

Supplementary data can be obtained with geophysical seismic (ground echo) or electrical resistivity tests, and with ground-penetrating radar. Simplest to interpret

is the radar that prints out a running log as the instrument is being pulled over the ground, but a limitation is that the depth scale depends on the moisture content, and penetration is limited.

Most important can be observations of soils and rocks exposed by erosion and occurring in outcrops and excavations. Airphotos and drone photos can reveal patterns that are easily overlooked from the ground. Interpretation depends on a sound knowledge and appreciation for geological origins.

1.2. Two Classes of Foundations

Foundations are described as shallow if they bear on near-surface soils or rocks, and deep if they extend down to firmer soil layers or rock. Deep foundations are more likely to be used to support heavy structures such as multistory buildings, and can be effective even if bedrock support is not available. Shallow foundations may be suitable for supporting lighter weight structures, depending on the firmness of the soil.

Support of Deep Foundations

Two sources of support for a deep foundation are end bearing at the base and shearing resistance along the sides, usually referred to as a *skin friction*. As the contributions involve different soil properties and are unlikely to peak out together, they are analyzed and/or measured separately, as side resistance often peaks out and starts to decline before end bearing is fully mobilized. A further complication is that if the ground settles, usually as a consequence of lowering the groundwater table, then skin friction is reversed, so it pushes down instead of up.

Expansive Clays Can Be Expensive Clays

Near-surface soils in many areas of the world often include clay minerals that expand when wet and shrink when dry, affecting pavements and foundations. The problem is intensified because dry weather is preferred for construction, when the clays are dry and deceptively hard but poised and ready to expand. Floors and foundations usually are raised unevenly, so walls develop diagonal cracks, and door and window frames can be distorted so they no longer are rectangular.

Expansive clays are the most costly problem in geotechnical, highway and foundation engineering, with a tally running into billions of dollars annually in the United States alone. But there are remedies and solutions.

End Bearing on Rock

Solid rock can be an ideal support for foundations but basement excavations may be too costly to be practical. Solid rock can lay buried underneath weathered rock and rock fragments and/or geologically younger soil deposits, so these can be penetrated with borings or driven piles that may require end protection with hardened steel tips.

A particularly serious problem can be shallow underground caverns or mine openings that remain undetected until a heavy load is applied. Caverns are created in limestone where infiltrating seepage water that has been rendered slightly acidic by dissolved carbon dioxide and concentrated at a groundwater table. The caverns therefore may be relatively deep and difficult to detect. In geological time as nearby valleys

are eroded deeper, the groundwater level is lowered, so caverns become accessible for spelunking. However, vertical channels appropriately called “glory holes” may connect different cavern levels.

Even shallow limestone may hold some surprises if it has been weathered along vertical fractures that become filled with clay. As this is associated with surface weathering and development of a “soil profile,” it is discussed later in this chapter. It is the shallow clay pockets, caverns, and mine openings that are most likely to cause problems.

Ground Improvement

Ground improvement means to improve what is there. A simple procedure is to let a pile of soil stand in for a future foundation until settlement stops, then remove the soil and build the structure. This procedure is particularly useful when a series of similar structures such as apartment houses are to be constructed so that after settlement is complete, the soil can be moved on to the next site. Engineering still is required to determine an appropriate preload pressure, measure settlement, and determine if a well system may be required to assist in the removal of water as it is squeezed out of the soil.

Dynamic compaction: Layers of soil can be spread and compacted with rollers or vibrators to create a structural fill. This procedure can dominate cut-and-fill operations for roads and highways, and can be used for foundations. Careful selection of a satisfactory fill soil is required, and standardized test procedures are used to determine appropriate soil moisture content and acceptance criteria for testing and compaction.

Deep dynamic compaction is more likely to be used to process soil in situ in preparation for a future foundation load. It involves using a crane to repeatedly lift and drop a heavy weight to pound the soil into submission. It is best adapted to rural areas.

Chemical soil stabilization can be achieved by mixing soil, Portland cement, or chemical lime prior with soil and compacting it in layers. For deep in situ stabilization, the lime can be introduced into open borings or mixed with the soil in situ in the borings. Lime reacts chemically with expansive clay minerals, so they harden and become non-expansive.

Procedures for ground improvement have received considerable attention in recent years, and are discussed in more detail in the last chapter in this book.

1.3. Residual Soils

Granite mountains are the ultimate source for most sand. Most granite is igneous rock, which means that at one time it was molten, and then slowly solidified at great depth. Therefore, individual crystals are sand-size and larger. Clear grains are quartz, and pink or white grains are feldspars that are more readily weathered to form clay. As feldspars chemically weather to clay, the grains expand, and granite becomes separated into grains of sand.

Travel Is Wearing

Sand is readily moved by gravity, wind, or water. Close to the source, the sand usually has about the same color as granite because it has the same mineralogical composition, about 25 percent quartz and the remainder feldspars. Farther from a



FIGURE 1.1 Granite is a major component in most mountain ranges and disintegrates along cracks to leave rounded boulders and sand. (Image source: *Geotechnical Engineering: Soil and Foundations Principles and Practice* by Richard L. Handy and Merlin G. Spangler. McGraw-Hill Educations © 2007.)

source, as feldspars weather and are degraded the mineral percentages are reversed, about 75 percent feldspar and the remainder quartz, with a characteristic tan color from grains being coated with iron oxides and clay. An exception is “Ottawa sand” that is a fossil beach sand and is almost pure quartz. One use is to make glass.

Weathering along cracks in granite leaves rounded boulders, as shown in Fig. 1.1. They obviously have not been rounded by rolling along in streams, as commonly assumed. As a general rule, rocks form mountains, which weather and disintegrate into soil that is moved downhill by water and gravity into adjacent valleys where they can be further modified by weathering or moved along by wind and water.

1.4. Soil Layers Created by Weathering

Topsoil “A Horizon”

Topsoil is preferred for gardening but not for engineering, as it contains organic matter that can separate grains and weaken the soil. Topsoil typically is 1–2 ft (0.2–0.5 m) thick unless eroded. At a construction site, topsoil usually is stripped off and saved for later use as a top dressing for lawns. Topsoil may be black from organic matter, and brown or red-brown from iron oxide coatings on soil grains. When developed under trees it can have a thin gray or white layer because of intense weathering from acid soil conditions.

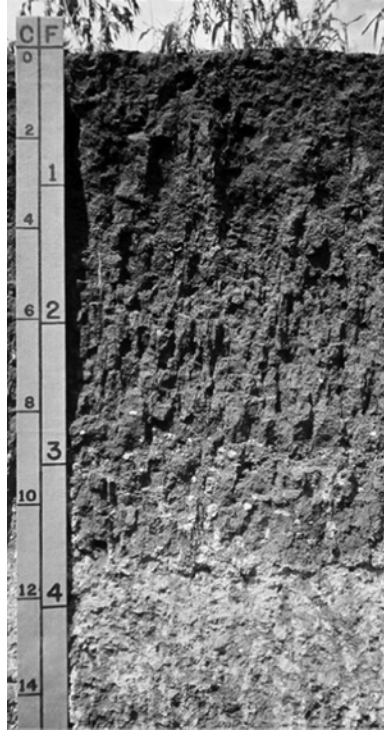


FIGURE 1.2 A weathered soil profile in expansive clay: Dark, organic A horizon topsoil about 8 in. (20 cm) thick on top of brown, clayey B horizon subsoil that has a blocky structure indicative of expansive clay. *Olton soil series in western Texas.* (Image source: USDA.)

Subsoil “B Horizon”

Clay that is created by weathering in the overlying A horizon can be carried down with infiltrating rain water to be deposited and concentrated in a relatively thicker subsoil layer called a “B horizon.” In temperate climates, B horizons commonly contain concentrated *expansive clay minerals* that shrink when dry and expand when wet. This can cause major problems in engineering.

Shrinkage Cracks and Blocky Structure in Expansive Clays

Vertical shrinkage cracks can define an “active layer” of shrink–swell cycling in expansive clay soils. In a B horizon the cracks can intersect to form a characteristic “subangular blocky” soil structure, as shown in Fig. 1.2. Blocks are coated with thin layers of expansive clay called “clay skins” that prevent bonding, so the soil is avoided for use in foundation engineering.

Case history. Expansive B horizon clay soil was recognized and removed from a building site. The pile of soil was not recognized as being expansive and was used as fill soil for another building site, with predictable consequences.

1.5. Vertical Mixing in Expansive Clay

In areas with extended dry seasons, vertical shrinkage cracks can extend a meter or more deep and can define an *active layer* in expansive clay. Cracks are an open invitation for debris and soil that slough off and prevent closing. Repeated open–close cycling then can build up sufficient lateral stress that exceeds the soil unconfined compressive strength, and the soil shears *along inclined planes*.

Shrink–swell cycling, therefore, can eventually mix the A–B horizons into a single thick layer that is expansive and black. The soils have been appropriately referred to as *black cotton soils*. The scientific name is *Vertisol*, for vertical mixing. The soils are bad news for engineering. A clue can be above-ground burials in cemeteries. Various methods can be used to deal with such soils and are discussed in Chap. 4.

1.6. Influence from a Groundwater Table (or Tables)

The level to which water rises in a well defines the groundwater table. It is replenished by seepage so the groundwater level tends to be a weakened expression of hillside surface elevations. Saturation of soil under a groundwater table reduces soil unit weight about one-half; therefore, it can have a major influence on engineering uses as well as contributing to wet basements.

The elevation of a groundwater table obviously is important in engineering, and can be measured from the water level in borings that have been left open for a day or more. The measurements usually are made with a tape that employs an electrical contact.

Groundwater Table and Soil Color

The elevation of a groundwater table can change seasonally depending on rains. Soil below a permanent groundwater level develops a diagnostic gray soil color and is referred to as “unoxidized,” as the gray color is attributed to a lack of oxygen dissolved in the water. Infiltrating rainwater contains dissolved oxygen that can react with iron compounds that stain soil grains to a shade of tan or brown. A seasonally changing groundwater level creates a mottled mixture of gray and brown, sometimes with vertical lines of rust concentrated along former root channels.

A color determination has obvious relevance in engineering as it can indicate seasonal variations in the level of a groundwater table. The examination of soil color should proceed and be recorded soon after the soil has been removed from a boring because it can rapidly change upon exposure to air.

Some guidelines for soil color are listed in Table 1.1. *It will be noted that soil color is not revealed by probing.* A more detailed identification can be made using color charts in the Munsell system, and charts showing only colors commonly found in rocks and soils are available from suppliers.

A Perched Groundwater Table

Downward seepage of water through soil may be impeded by a buried layer of clay to create a “perched” groundwater table that is separated from a deeper and more permanent groundwater level. The clay layer often will represent a former ground surface

Black, dark brown	Organic topsoil or <i>A horizon</i> . Avoided in engineering.
Thin, light gray or white	Indicates acidic conditions in soil developed under forest.
Tan or brown	Most common, having been oxidized by exposure to air and therefore above a groundwater table.
Mottled brown and gray	<i>Fluctuating groundwater table</i> . Important to recognize in engineering, seasonal changes in buoyant support reduce shearing resistance.
Gray	(a) Most commonly indicates reducing conditions from a lack of oxygen below a permanent groundwater table. (b) May be “fossil” in geologically young glacial soils that have been highly compressed and rendered impermeable by a heavy weight of glacial ice.
Blue or green	Excessive reducing conditions indicating marshy conditions. Can be an important clue to a gas leak. Also can occur in soil after prolonged contact with a bituminous pavement.
White, crusty	<i>Caliche</i> : Concentrations of calcium carbonate formed in near-surface soil where the rate of evaporation exceeds the rate of precipitation. Characteristic of near-surface soils in an arid or semiarid climate.

TABLE 1.1 Some Guidelines for Soil Color

with buried *A* and *B* horizons that are called *paleosols*, for ancient soils. A perched groundwater table can be troublesome, as it can drain into an open excavation.

1.7. Intermittent Recycling

Many soils used in engineering are *sediments*, with properties that are defined by their geological origins. In geological time, sediments become compressed and cemented to form sedimentary rocks. Most common is *shale*, which typically is gray, dense, and thinly layered from having been deeply buried prior to being exposed by geological erosion.

Most shales are deposits from shallow seas that covered areas of continents during past geological time. Rocks that are not thinly layered and are composed of clay are *claystones*. Shale usually is dominant, and often is interlayered with sandstone, limestone, and coal.

Shales of intermediate geological age are less likely to be thinly layered and may contain expansive clay minerals and occasional dinosaur tracks. Thin layering is not a criterion for expansive or non-expansive clay.

1.8. Soil Types and Foundations

The simplest foundations are *slab-on-grade*, concrete slabs that are flat and level. If a foundation slab covers expansive clay, the slab will restrict evaporation, and therefore moisture accumulating under a central area will expand the clay and lift the center part of a structure more than the edges. Expansive clay problems are discussed in Chap. 4. *Shallow foundations* extend down through topsoil, but still can be affected by expansive clays.

Column foundations usually are square but can be round. As discussed later in this chapter they can be hit-or-miss when founded on weathered limestone. *Wall foundations*

are linear and more likely to bridge across weak areas. Shallow foundations are commonly used for supporting lightly loaded structures.

Deep foundations initially were straight tree trunks that were stripped of bark and branches. They usually are driven upside-down to take advantage of a natural taper, and still are widely used. Driven piles used to support heavy structures are more likely to be steel or concrete. Steel piles can be pipes, H-beams, or hollow and tapered.

Concrete piles can be driven, or they can be larger in diameter and bored-and-poured. Resistance to lateral forces can be increased by incorporating a “cage” of steel reinforcing that is lowered into the concrete before it sets.

In caving soils that do not hold an open boring, an *augercast pile* is created by twisting a hollow auger that is the full length of a pile into the ground, so soil between the spirals holds the boring open. As the auger is raised, cement grout is pumped down through the center pipe to create a pile from the bottom up. Positive fluid pressure is maintained to prevent caving.

Two classes of deep foundations are end-bearing, which transfer load down to a hard stratum such as bedrock, and *friction* that transfer load to soil that is in contact all along the surface. However, the definition is not exclusive because both mechanisms can contribute, but is highly unlikely that the two resistances will develop and peak out together.

Three consolidation classes of soils: As soil tends to consolidate under its own weight, it typically becomes more supportive with increasing depth. A soil that has been consolidated to equilibrium under existing overburden pressures is said to be *normally consolidated*. Its density and unit weight, therefore, increase with depth.

A soil that has been consolidated under a prior larger overburden pressure is *overconsolidated*. Overconsolidation is advantageous because it can reduce and even prevent significant foundation settlement if the foundation pressure is less than the prior overburden pressure. Some *quasi-elastic* settlement will occur. Overconsolidation can occur with a single emergence–submergence cycle of a groundwater table, so the ideal, normally consolidated soil may be difficult to find in nature.

A soil that is *not* in equilibrium with the existing overburden pressure is said to be *underconsolidated*. This obviously is a potentially unstable condition because if conditions change, the soil may consolidate. In recently deposited soil, the time after deposition may not be sufficient to allow drainage of excess pore water. In that case consolidation is on-going and can be expected to speed up with additional loading. The other common cause for underconsolidation is most likely to be encountered in wind-deposited loess soil, where grains are pulled together by negative (capillary) pressure that can be lost upon saturation with water.

Influence of a Groundwater Table

Even though water can only occupy pore spaces between soil grains, about half of the weight of soil that is under water is supported by buoyancy. As the elevation of a groundwater table depends on the availability of water, it can vary seasonally. However, it is a first-time lowering of a groundwater table that can be most damaging because the soil may be subjected to a load that it has not experienced before. This is most likely to occur in cities, where a surface cover drains carry water away instead of allowing it to penetrate into the ground.

As lowering of a groundwater table removes buoyant support for the soil, even deep foundations such as piles can be affected because if the soil settles